UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGIC INVESTIGATION OF FAULTING NEAR THE NATIONAL REACTOR TESTING STATION, IDAHO

by
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With a section on MICROEARTHQUAKE STUDIES

by
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This report has not been edited or reviewed for conformity with Geological Survey standards and nomenclature

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U.S. Atomic Energy Commission

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Background of study

At the request of the Division of Reactor Development and Technology, U.S. Atomic Energy Commission, the U.S. Geological Survey made a reconnaissance from October 23 through November 4, 1967, to investigate the potential for faulting and strong earthquakes near the National Reactor Testing Station (NRTS). This reconnaissance was done by M. G. Bonilla and G. H. Chase, and it resulted in the finding of various sites near the NRTS in which several kinds of geologic features indicated faults.

Bonilla and Chase (written commun., 1968) noticed conspicuous scarps in alluvial fans extending several miles along the flanks of mountain ranges north of Arco and Howe. They interpreted the Arco and Howe scarps to be consequences of geologically young faulting (fig. 1).

Figure 1.—In pocket.

Bonilla and Chase thought that a third scarp immediately north of Mud Lake, which had been previously attributed to faulting (Stearns and others, 1939, pl. 3, p. 43), might mark an active fault by reason of an earthquake felt nearby in 1911. The other geologic features examined by Bonilla and Chase at the NRTS are lineaments several miles long on the lava plain, principally a lineament that reaches about 17 miles northward from East Butte. Such lineaments displayed nothing surely caused by faulting, and Bonilla and Chase accordingly considered them to be features that probably formed during emplacement of the lava.

Bonilla and Chase recommended additional geologic study to test their tentative conclusions from the evidence then available that geologically young faulting has occurred near the NRTS, and that the potential for strong seismic effects at the NRTS is greater than heretofore supposed. They recommended further that portable seismographs be installed to determine whether small earthquakes are detectable along the fault scarps. Although Bonilla and Chase decided that the lineaments on the lava plain at the NRTS probably are not a consequence of faulting, they prudently recommended that geologic work be done on the origin and age of the lineaments as a basis for predicting their future behavior.

The Division of Reactor Development and Technology thereupon authorized the U.S. Geological Survey to make further geologic and seismologic studies. This report gives the results of geologic investigations made from September 1968 through August 1969, together with the results of seismologic investigations made from December 1968 to September 1969.

 (p. 3a follows)

These investigations were designed to obtain detailed information only on the conspicuous scarps and lineaments found by Bonilla and Chase. That is, the investigations were not intended to provide a complete assessment of all possible features suggestive of potential faulting near the NRTS. Thus, the scarps north of Arco and Howe, together with the scarp at Mud Lake, were selected for detailed study because they are the most obvious potential sources for large earthquakes near the NRTS. Information was clearly needed to evaluate whether the scarps had indeed formed by faulting. If so, further information was needed on the ages and displacements of particular faults. Similarly, the lineaments recognized by Bonilla and Chase needed to be studied in detail; their possible relation to faulting was in doubt, and the principal lineament was a cause for concern because it passes near an existing reactor facility.

Fieldwork

Geology

In the geologic study for this report, prior knowledge of the regional geology was applied, especially information about landforms, soils, and erosion by which young geologic events are dated.

The Arco and Howe scarps were examined on foot to trace their length and to define the distribution, nature, and ages of the associated sedimentary deposits and soils. These scarps were then trenched at selected sites to expose faults associated with the scarps as well as the related geologic details of subsurface stratigraphy and structure. Particular attention at the trenches was given to measuring amounts of displacement on recognizable faults and to determining the episodes and probable ages of fault movements.

The scarp north of Mud Lake was also examined on foot to identify the exposed rocks and their stratigraphy. Subsurface features of the scarp at Mud Lake were investigated by drilling.

Several lineaments on the lava plain were traced out on foot and were then trenched at selected sites. The lineament that trends through the site of the Experimental Breeder Reactor II (EBR II) was given special attention to ascertain whether it presents an identifiable geologic hazard.

Although the fieldwork was focused almost entirely on the Arco and Howe scarps, the Mud Lake area, and the lineaments on the lava plain, intermittent study was done along Henrys Fork and the Snake River from Ashton to American Falls to examine terrace deposits and their soils. By comparing these soils of known age with soils found at the faults near the NRTS, the ages of faulting were more closely estimated.

Seismology

From December 1968 to September 1969, six portable seismometers were arrayed in a network around the NRTS by the U.S. Geological Survey's National Center for Earthquake Research (fig. 1). This network was installed to detect small and moderate earthquakes that might occur in this area and to locate these earthquakes with respect to geologic structures. The network, synopsis of data, and locations of epicenters are discussed in a separate section of this report by A. M. Pitt and J. P. Eaton.

Acknowledgments

This report was prepared as part of a research program by the U.S. Geological Survey on geologic, seismologic, and hydrologic factors that pertain to the design of nuclear facilities and to the selection of their sites. This program is sponsored by the U.S. Atomic Energy Commission, Division of Reactor Development and Technology, under W. G. Belter, Chief of the Environmental and Sanitary Engineering Branch. The Idaho Operations office of the AEC, under W. L. Ginkel, Manager, provided heavy equipment and operators for the trenching.

The geologic work was facilitated in many ways by personnel at the NRTS. Special thanks are due the foremen and operators of the excavating equipment, who managed to complete the required trenches under unfamiliar conditions. They faced the inevitable mechanical misfortunes with equanimity and twice dealt with the frustration of being deeply mired with 90 tons of equipment in bottomlands of the Little Lost River. Radio-equipped vehicles supplied at times by the Motor Pool made calls for help possible in such difficulties, and the vehicles were a considerable convenience in other obvious ways. Cooperative assistance at every turn was also received from Dr. G. L. Voelz, AEC, and J. T. Barraclough, Geological Survey, and their associates. Without this constant help from the NRTS staff, the fieldwork never could have been completed.

At various times, I benefited from consultation in the field with members of the U.S. Geological Survey staff, including E. H. Baltz, J. T. Barraclough, M. G. Bonilla, E. H. Crosthwaite, A. H. Harder, J. B. Robertson, R. Schneider, S. Subitzky, and H. H. Waldron.

My understanding of soils near the NRTS was improved by advice in the field from J. O. Harwood, Soil Conservation Service.

Lastly, G. T. Stone, The University of Oklahoma, generously provided the results of his technical study of lavas at Mud Lake.

Summary of conclusions

Well-defined high-angle faults were exposed by trenching across scarps in alluvial fans along mountain ranges north of Arco and Howe, Idaho, a few miles from the NRTS boundary.

The Arco scarp coincides with a zone of closely spaced faults in alluvial fans along the western foot of the Lost River Range. It extends northward about 10 miles from Arco. The southern end of the scarp has been eroded by the Big Lost River, and the northern end merges into an unstudied scarp in bedrock. As a topographic feature, this range-front fault zone has a length of more than 20 miles, of which the Arco scarp is the southern part. As determined by trenching in alluvial fan deposits at one place on the Arco scarp, multiple movements in the fault zone have resulted in an aggregate vertical displacement of at least 40 feet. Measured offsets of stratigraphic units within the fault zone indicate at least two episodes of vertical movement on individual faults. One episode of movement caused a minimum vertical offset of 15-20 feet, and another offset was more than 10 feet.

The Howe scarp coincides with a zone of closely spaced faults in alluvial fans along the western foot of the Lemhi Range. A southern segment of the scarp follows the southern part of the range a distance of 9 miles, and a northern segment is at least 4 miles long. These segments are separated by a bedrock ridge 2 miles wide in which the scarp is indistinct. As determined by trenching in alluvial fan deposits at one place on the southern segment, multiple movements in the fault zone have resulted in an aggregate vertical displacement of at least 50 feet. Measured offsets of stratigraphic units in the fault zone indicate four or more episodes of vertical movement on individual faults, ranging from 1 foot to more than 10 feet.

 (p. 8a follows)

The hazard represented by the fault displacements measured at the Arco and Howe scarps can be appreciated from records of historic earthquakes caused by movement on fault scarps in the Rocky Mountains and the Basin-and-Range province. (See Bonilla, 1967, for a summary of earthquakes caused by historic faulting in the United States.) For example, the 1959 Hebgen Lake earthquake in Montana (Richter magnitude 7.1) was accompanied by vertical ground-surface displacements of as much as 20 feet along prehistoric scarps. Surface displacement on the main fault occurred along a length of 15 miles. In Nevada, the 1954 Fairview Peak and Dixie Valley earthquakes (Richter magnitudes 7.1 and 6.8, respectively) were accompanied by vertical ground-surface displacements of from 7 to 12 feet along prehistoric scarps. The surface displacements on these faults were 36 and 38 miles long, respectively, Also, during the 1934 Hansel Valley earthquake in northern Utah (Richter magnitude 6.6; Eppley, 1965, p. 58), ground-surface displacements of nearly 2 feet were observed on a fault segment about 5 miles long.

For the Arco and Howe scarps, although the total lengths of particular faults cannot be readily determined, the overall lengths of the scarps and the measured amounts of individual displacements are comparable to such features seen at places of historic faulting in Montana, Nevada, and Utah, as explained above. By this analogy, the faulting that accounts for the Arco and Howe scarps must have been accompanied by large earthquakes.

Faulting in the alluvial fans near Arco and Howe is geologically young. However, the total displacements of underlying bedrock caused by vertical movement on the range-front faults amounts to thousands of feet, and the ages of the displaced bedrock show that the first movements began millions of years in the geologic past. Thus, the observed faults in the alluvial fans are merely a result of the latest of many episodes of movement. To avoid underestimating the geologic hazards shown by these faults, the time of latest faulting is assumed in this report to be possibly as young as allowed by the available field evidence. Thus, at both the Arco and Howe scarps, the evidence indicates faulting in the last 30,000 years, possibly more recently than 10,000 years ago, and movement within even the last 4,000 years cannot be ruled out. Because the probability of renewed faulting along the Arco and Howe scarps is directly related to the decreasing age of the visible faults, this evidence of geologically recent movements implies a greater risk for future earthquakes than do the older displacements.

In summary, the lengths and displacements on the Arco and Howe scarps, together with the evidence for geologically recent movements, indicate that large earthquakes related to renewed faulting along these scarps might recur at any time in the future.

The scarp that overlooks the north shore of Mud Lake consists of fine-grained sedimentary deposits on the east (Clay Butte) and two layers of basaltic lava on the west, separated by detrital deposits. Drilling shows that the lower lava is concealed in Clay Butte, and talus from this lava is buried by sedimentary deposits near the shore of Mud Lake. The various deposits and lavas penetrated by drilling fail to show that any geologic unit has been demonstrably displaced by a fault along this scarp. However, because the geologic history of Mud Lake is still inadequately known, the possibility of faulting cannot be completely ignored, even though remote. Thus, if sensitive installations are planned for construction near Mud Lake, further geologic investigation would be prudent.

The lineaments examined on the lava plain at the NRTS present no identifiable geologic hazards. The principal lineament that trends northward from East Butte is marked by a surficial streak of sand that crosses numerous undisturbed irregularities that formed during eruptions of the lava. Excavation across the streak shows an unbroken lava surface. Another trench across a shorter but analogous lineament that passes through the site of Experimental Breeder Reactor II also shows undisturbed lava. Excavation in surficial deposits at one of the lineaments that trend northeast from Middle Butte reached the underlying basalt at two places, neither of which displays any disruption of the initial lava surface.

The NRTS network of seismographs, during its 9 months of operation, did not locate a single earthquake within a distance of 70 km. Moderate activity, however, was detected in a zone about 100 km north of the NRTS and in a zone about 150 km northeast that includes the locus of the Hebgen Lake earthquake of 1959 in Montana (Richter magnitude 7.1). Large earthquakes might occur anywhere in these active zones. The absence of detected earthquakes at the NRTS does not disprove the possibility that strain in the earth's crust could produce slippage on a nearby fault and thus generate a large earthquake.

Arco scarp

General features

The Arco scarp is a subdued cliff-like step about 25 feet high that interrupts the slope of alluvial fans where the Lost River Range faces the Big Lost River Valley north of Arco (fig. 2). In profile,

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Figure 2.--NEAR HERE.

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the angle of slope along the Arco scarp varies between 20° and 25°, in contrast with slopes of about 5° on the adjoining fans. This contrast in slope, together with a general straightness, makes the scarp conspicuous both at ground level and from the air. The scarp traces the outline of the mountain range within a few hundred feet of outcropping bedrock from Arco northward a distance of 10 miles. Topography suggests that this range-front scarp extends at least an additional 10 miles north. As discussed below, excavation across the Arco scarp 6 miles north of Arco reveals that the scarp coincides with a narrow zone of high-angle faults. Former vertical displacements on these faults evidently produced an abrupt topographic relief, now softened in contour by natural erosion but still recognizable as the Arco scarp.

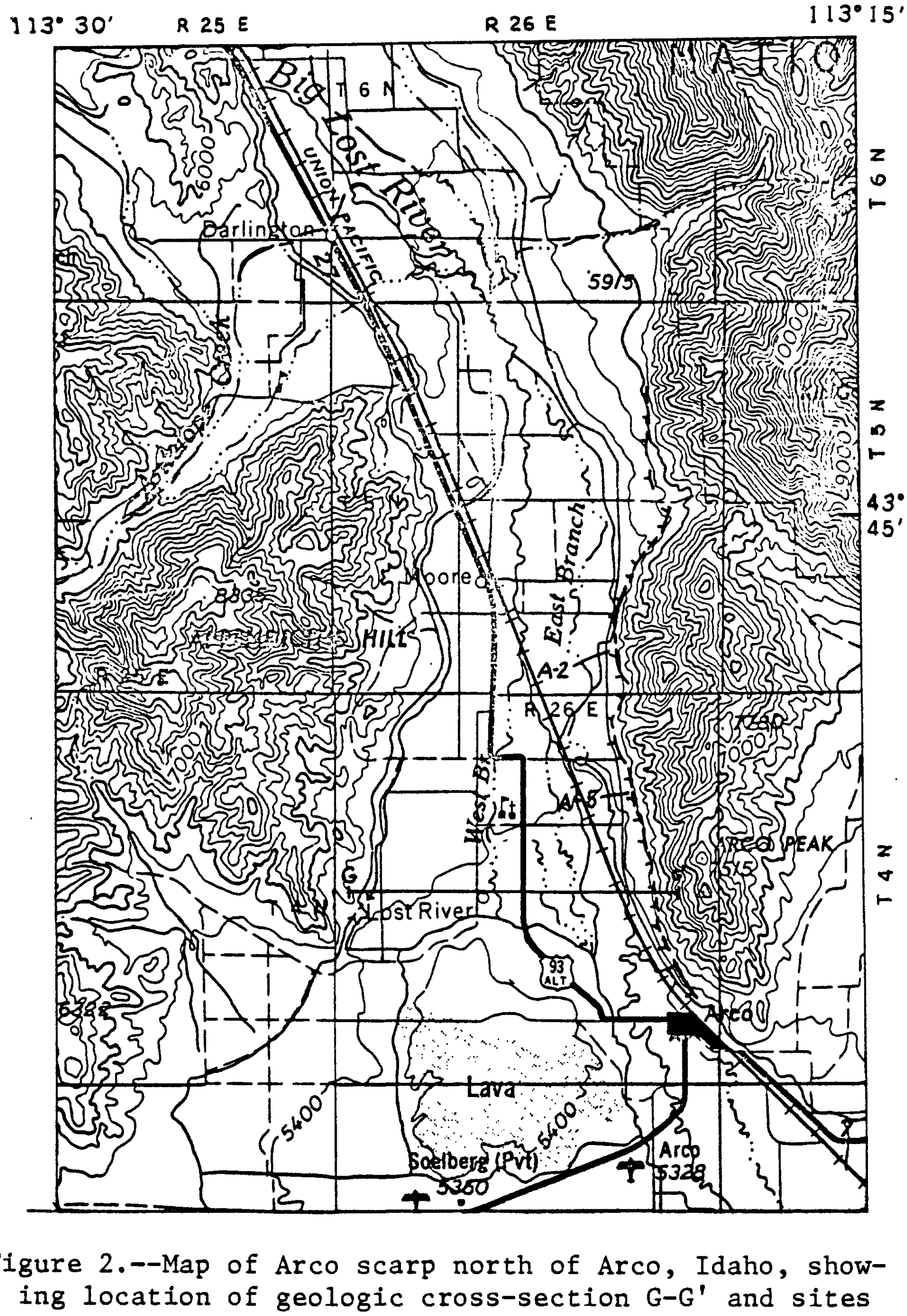

Figure 2.--Map of Arco scarp north of Arco, Idaho, showing location of geologic cross-section G-G' and sites A-2 and A-5 discussed in the text. Intermittent gaps in the scarp line are places where the scarp continuity is interrupted by alluvial fans younger than the scarp.

Alluvial fans above (east) and below (west) the Arco scarp have subtle differences in soils, vegetation, and erosional aspects that further tend to emphasize the scarp. Coupled with topography, these differences show that the scarp is not continuous but is instead a series of segments ordinarily 500-1,000 feet long interrupted by scarp-free gaps commonly 100-300 feet wide. The higher alluvial fans east from the scarp are dissected by gullies 10 feet or more deep and are covered by drought-resistant vegetation (chiefly black sagebrush, shadscale, and horsebrush) that is rooted in caliche soil. At the toe of the scarp are alluvial fans with inconspicuous shallow gullies a foot or two deep, and these low fans generally support plants less tolerant of drought that grow in soil not notably cemented with caliche. These lower fans spread outward from gaps that interrupt the continuity of the Arco scarp. That is, the Arco scarp is expressed by an abrupt rise to higher, apparently older, alluvial fans, and it is interrupted at gaps occupied by lower, apparently younger, alluvial fans. The ages of these respective fans thus pertain to the age of the Arco scarp and its time of formation by faulting. The problem of dating the fans and the scarp is discussed at the close of this chapter.

Faulting at site A-2

A particularly straight segment of the Arco scarp (site A-2 near the center of sec. 35, T. 5 N., R. 26 E.; see fig. 2) was selected for study of its internal geologic features, partly because of accessibility for heavy excavating equipment, partly because some of the required earth moving had been previously accomplished by erosion along a perpendicular stream, and partly because this site is about midway along the length of the scarp and therefore could be expected to be representative of geologic relations that would be found elsewhere. Figure 3 is a vertical aerial photograph of the area of

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Figure 3 .--NEAR HERE.

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site A-2, and Figure 4 shows its appearance at ground level. The

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Figure 4 .--NEAR HERE.

Arco scarp at site A-2 is about 200 feet west of the nearest bedrock outcrops at the foot of the mountain range.

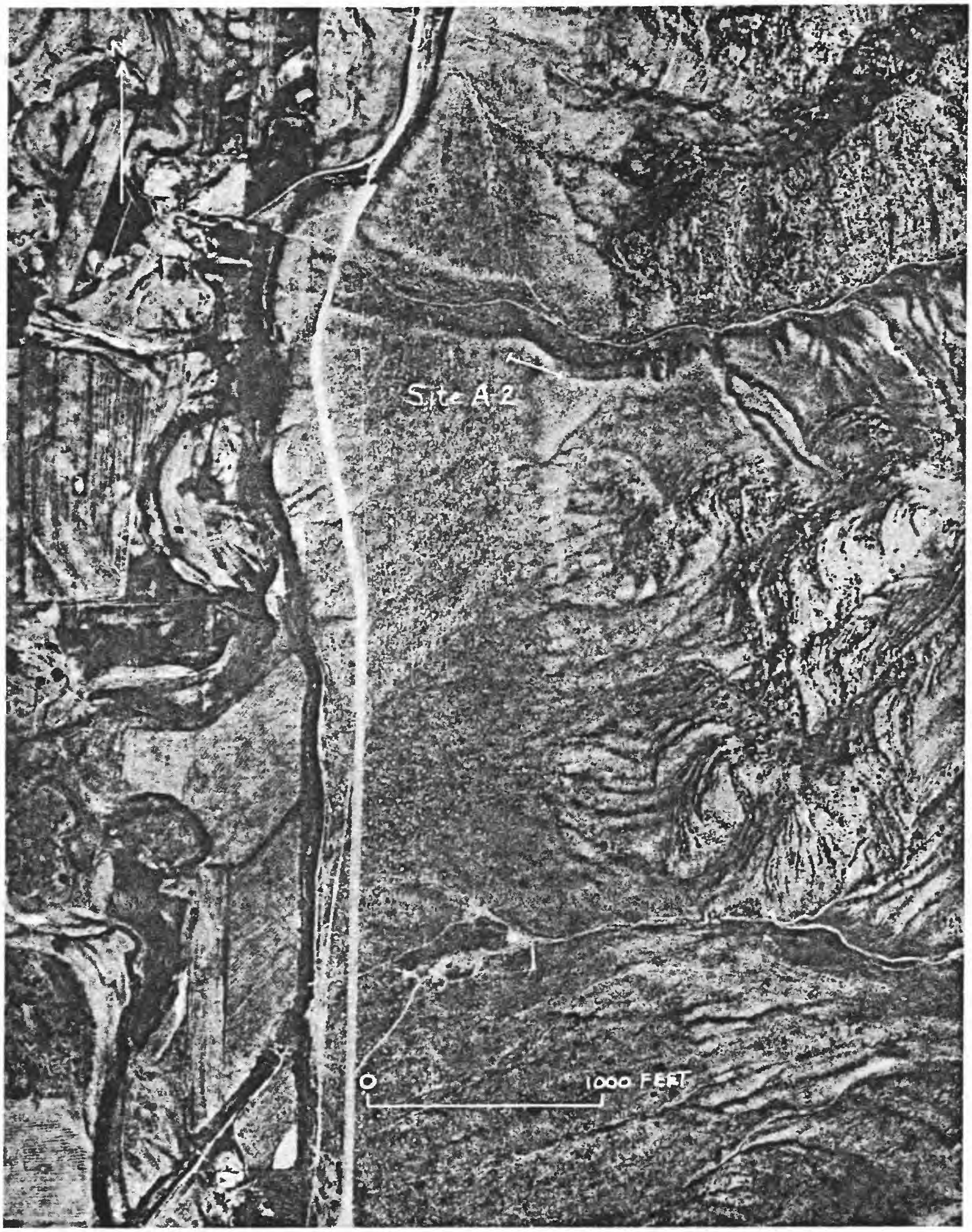

Figure 3.--Vertical view of Arco scarp in sec. 35, T. 5 N., R. 26 E., showing location of site A-2 on the south side of a stream perpendicular to the scarp. (Enlarged from U.S. Department of Agriculture aerial photograph CPP-3W-185 taken July 16, 1959.)

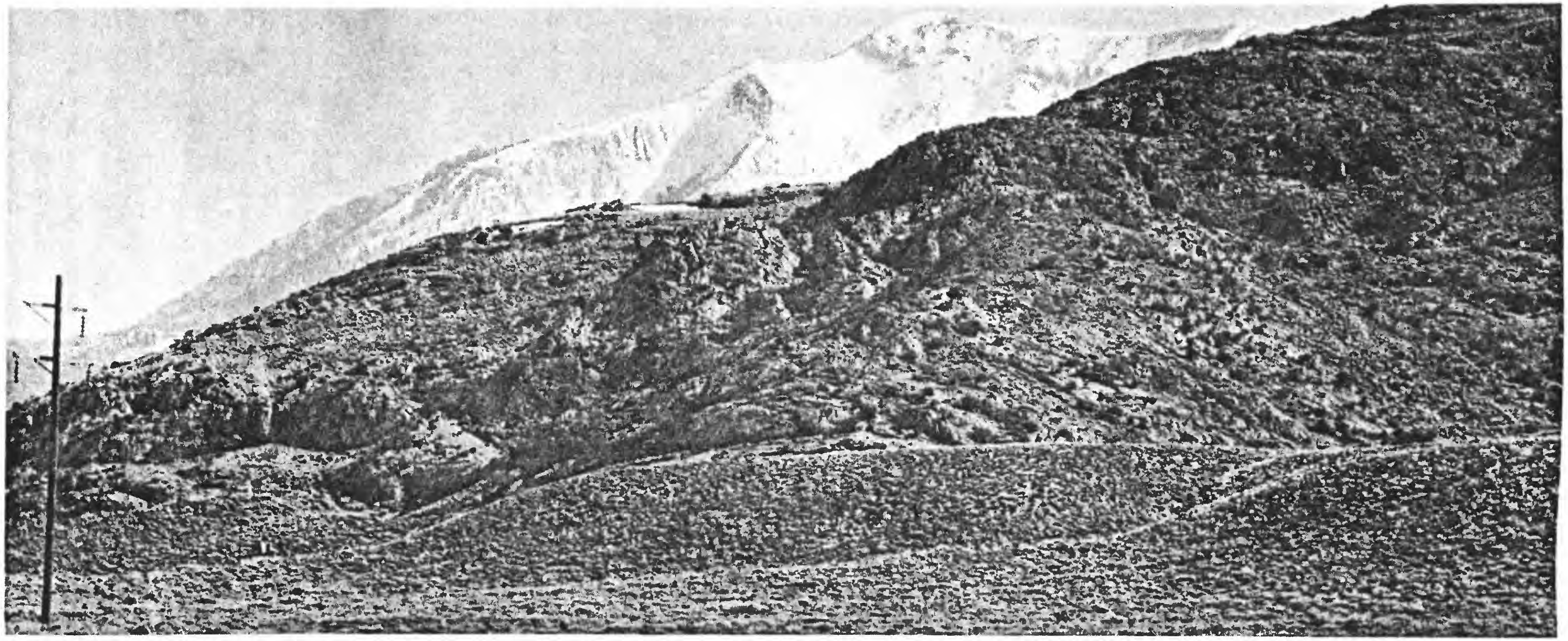

Figure 4.--View north-northeast toward Arco scarp in sec. 35, T. 5 N., R. 26 E. The scarp is a step 30 feet high in the general gradient of the adjacent alluvial fans, but the topographic relief from head to toe is about 50 feet. Site A-2 is near the left-hand side of this photograph, where the bulldozer can be seen.

With a large backhoe and bulldozer, a trench 25-35 feet deep and more than 170 feet long was excavated at site A-2 approximately perpendicular to the Arco scarp. A sketch of the geologic features in fan gravel thus exposed in profile is shown in figure 5. As in other

Figure 5.--NEAR HERE.

geologic diagrams, attempts to represent all the variable aspects of lithology and bedding would be needlessly confusing, and this sketch therefore emphasizes only the more distinctive lithologic units, large or small, that can be readily recognized and traced.

The sketch portrays bedded gravel on the west and east disrupted by a zone of high-angle faults located two-thirds the distance down the scarp face. For convenience of discussion, the principal fault planes (which are at most 2-3 inches wide as seen in this section) are designated by letters. Between faults A and B, including the western branch of fault A, the gravel has no bedding and consists of material churned by movement along these faults or otherwise disturbed during fault displacement. The bedded gravel between faults B and C matches the sequence of beds on the east and thus demonstrates about 2 feet of vertical displacement on fault C, the western side having moved relatively down. Also, the beds between faults B and C have an exaggerated westward dip, about 12°, and this circumstance indicates drag by downward relative movement of material on the west that was displaced on fault B. The excavated trench gives only a two-dimensional view of these faults and does not permit measurement of possible strike-slip movement, that is displacement in the direction of the scarp.

The fan gravel east of the faults is arranged in fairly regular thick beds that alternate between brown layers of limestone pebble to boulder gravel and open-textured gray layers of angular limestone pebbles. The brown layers have a matrix of sand and silt, which is represented on the sketch by a stipple pattern. The upper 15 feet (that is, the gravel above the highest bedding plane drawn between survey marks 15 and 21) is less conspicuously stratified but includes brown and gray layers of angular pebbles, rounded cobbles, and sand. These gravel beds dip westward at 5°. The fan gravel west of the fault zone extends upward to a conformable contact 12 feet below survey mark 9, and 7 feet below survey mark 5. (Above this contact are deposits of sand and colluvium related to faulting that will be discussed shortly.) This fan gravel lacks the continuous beds found east of the fault zone and is dominated by gravel of different character, namely gray lenticular layers of angular pebbles and cobbles that lack abundant interstitial sand and silt. The bedding planes dip systematically westward at 2°. The change in dip from 5° on the east to 2° on the west is apparently due to rotation during faulting.

Aggregate displacement at site A-2

The sketch illustrates an obvious fact, determined by close scrutiny during the week after the trench was first exposed (April 23-29, 1969), that no beds west of the fault zone match beds on the east. However, because only a small part of the upper 15 feet of gravel east of the fault zone is exposed, and because gravel in alluvial fans typically changes character in short distances, a possible match between this upper 15 feet of gravel and the lowest exposed deposits west of the fault zone cannot be categorically ruled out. Thus, by projecting westward the bedding plane at the base of this upper 15 feet of gravel, and by then measuring down to the base of the exposed beds west of fault A, a minimum vertical offset of at least 40 feet is indicated. Virtually all of this displacement was in the narrow zone of fault breccia and rubble between faults A and B.

Evidence of multiple movement

Study of details near these faults indicates that the aggregate displacement, whatever its magnitude, was accomplished during two or more episodes of movement. These details also demonstrate that each of the offsets exceeded 10 feet. The features to be described are between survey marks 8 and 11 on Figure 5. Their origin is interpreted in the diagrams of Figure 6.

Figure 6.--NEAR HERE.

Immediately west of fault A, at survey mark 10, a wedge of loose gray fault rubble is composed of angular pebbles and some cobbles. Virtually all the tabular pieces of this rubble lie on edge more or less parallel with the fault plane. From a present width of 5 feet at the top, the wedge pinches out downward against the fault plane at a depth of 25 feet. Adjacent to this wedge on the west is additional fault rubble, also gray and loose, but easily distinguished by its random distribution of stones. At survey mark 9, at a present depth of 12 feet, the fault rubble is abutted perpendicularly by the contact between fan gravel and overlying colluvial material that has inclined concave bedding (fig. 7). Still farther west, below the present

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Figure 7.--NEAR HERE.

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surface deposits, the old colluvium merges with eolian sand that also rests on the fan gravel.

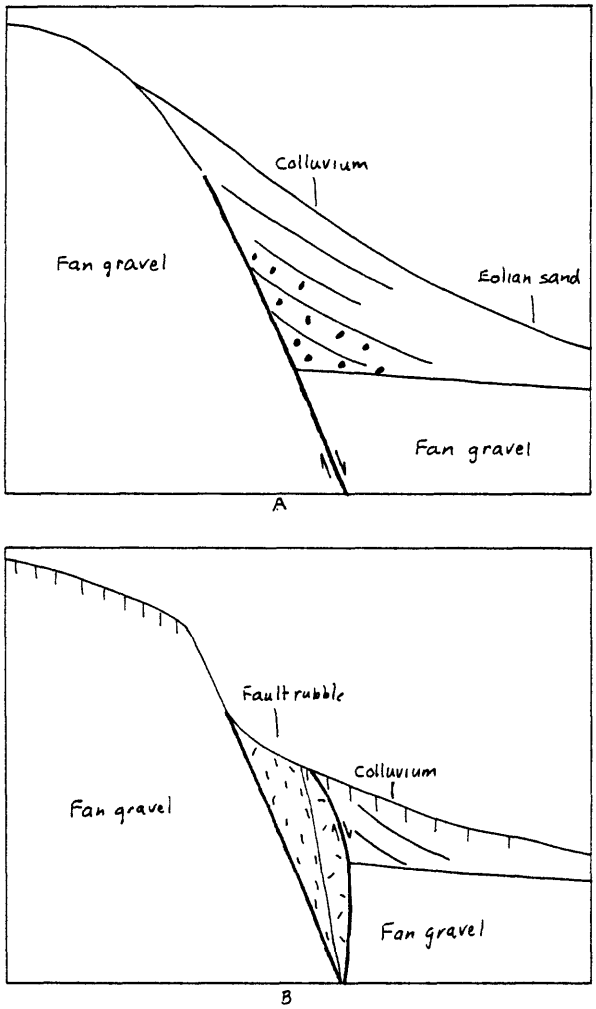

Figure 6.--Formation of the Arco scarp by faulting.

A. Movement in the zone now represented by Faults A and B displaced the original alluvial fan surface relatively downward on the west. Colluvium derived from the higher fault block was then deposited against the exposed fault face and mingled westward with eolian sand on the fan surface.

B. Further movement produced a gap occupied by fault rubble, and the old colluvium was displaced downward against this rubble. A caliche soil on the colluvium was possibly displaced by still later movement in the fault rubble.

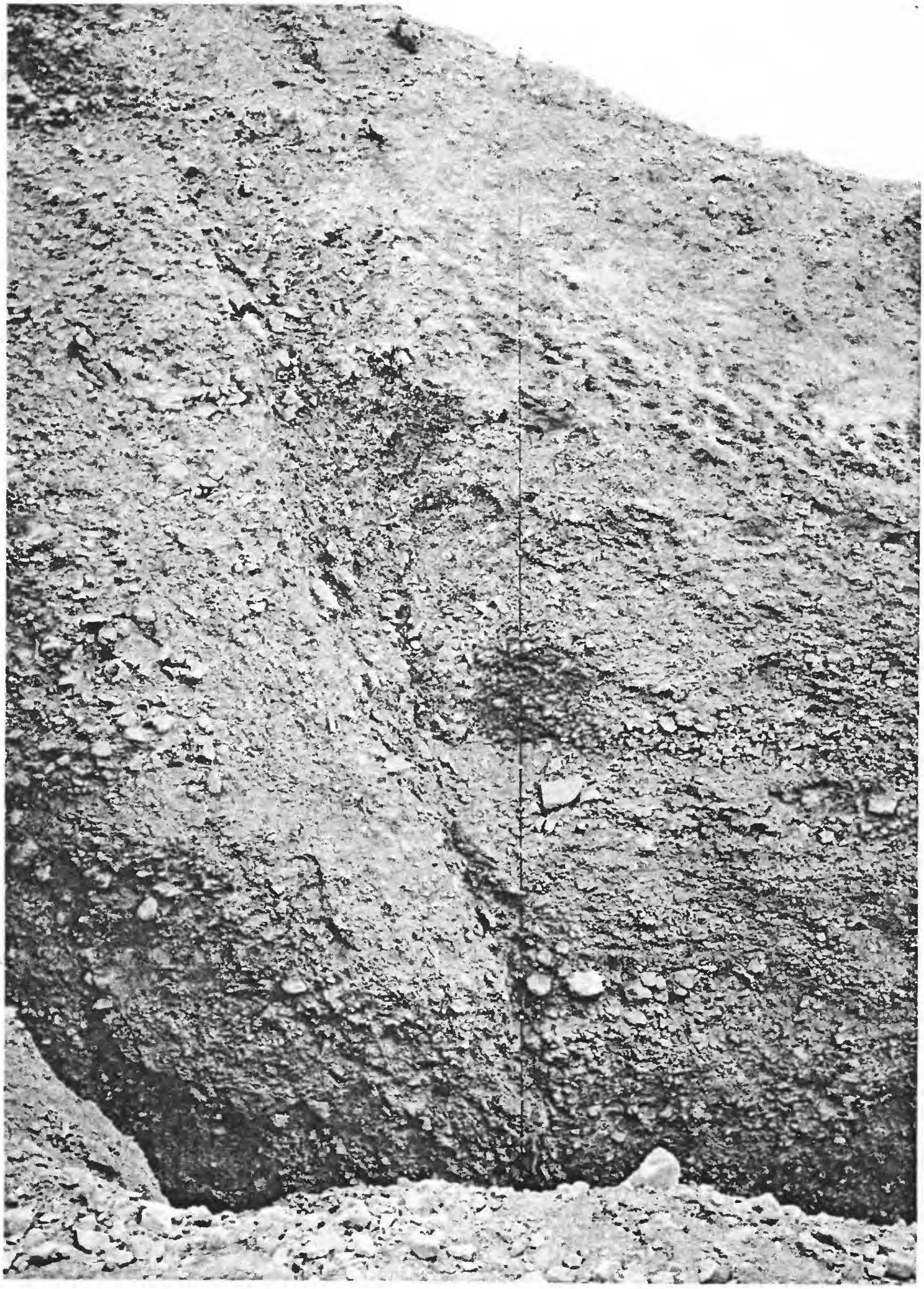

Figure 7.--Upper part of trench wall of site A-2 at survey mark 9, showing fan gravel and overlying colluvium on the west (right) against nearly vertical fault rubble. Marks on the vertical tape are 1 foot apart.

As shown on Figure 6 A, deposition of the old colluvium on the fan gravel was surely a consequence of at least one episode of faulting, because an exposed fault scarp in the gravel was the only possible source for the colluvium. A lack of soil on the fan gravel where it is buried by the colluvium indicates that this faulting occurred while deposition of gravel by a stream debouching from the mountains was still in progress. That is, the fan gravel west of the fault was linked with fan gravel upslope on the east at the time of faulting, even though this higher fan gravel has evidently since been removed by erosion. During buildup of the colluvium, stream deposition along the mountain front stopped in this immediate area, perhaps as a consequence of topographic changes brought by faulting, and eolian sand on the fan surface mingled with colluvium near the fault scarp. If the inclined bedding in the colluvium is projected upslope to fault A, given a preserved thickness of 10 feet, the minimum indicated initial scarp height (fault displacement) amounts to 15-20 feet.

The perpendicular intersection of loose fault rubble with the horizontal boundary between fan gravel and old colluvium at survey mark 9 demonstrates fault movement between the rubble and the adjacent deposits (fig. 6 B). The fault rubble is so loose that it never could have survived intact on a vertical exposure and thus produce the perpendicular intersection by ordinary deposition. (Indeed, this rubble began to crumble into the trench as soon as it was exposed by the excavating equipment.) In short, the steeply dipping contact at the west edge of the rubble is undoubtedly a fault. Because of the preserved thickness of the colluvium, displacement on this fault during a single episode of movement was at least 10 feet. It seems probable that the rubble was produced by this movement.

The colluvium and immediately adjacent fault rubble near survey mark 9 contain in the upper part conspicuous soft caliche that is visible to a depth of 3-4 feet (see the zone of light-colored streaks at the upper right of fig. 7). In the colluvium, the caliche forms a network of veins, some conforming with inclined bedding planes, others more or less vertical. In the rubble, the caliche occupies much of the space around stones but does not hold them tightly. This soft caliche rather clearly represents the lower part of the carbonate horizon of a thick calcareous soil. It is recognizable westward nearly as far as survey mark 6 but apparently ends abruptly on the east against the wedge of rubble at survey mark 10. The absence of caliche soil at the rubble wedge could be due to former steep topography along the fault scarp, which has now been subdued by erosion, thus obliterating part of the soil. According to this interpretation, a former slope that was mantled by caliche soil at the fault scarp would have been about as steep as the observed faults. Such a slope stable enough for soil formation is unlikely. More probably, the abrupt termination of the caliche was caused by faulting between the rubble wedge and soil-covered deposits on the west (fig. 6B).

In summary, an initial vertical displacement of at least 15-20 feet in a narrow zone of fault breccia, and a subsequent displacement of more than 10 feet are rather clearly indicated by detailed geologic features exposed at site A-2. Still later displacement of indeterminate amount is suggested by the abrupt terminus of a relic soil. Displacement of about 2 feet on a parallel fault 7 feet east (fault C on fig. 5) is associated with exaggerated dip in the intervening beds that expresses drag during movements on the principal faults (faults A and B on fig. 5). These displacements, together with other possible displacements not yet determined, aggregate at least 40 feet of vertical offset along the Arco scarp.

Age of faulting

Regional relations

All the alluvial fans that border this stretch of the Big Lost River are younger than basalt of the Snake River Plain southeast of Arco. This age relation derives from circumstances that account for the Big Lost River being incised in a gorge in the lava plain 50-75 feet deep and 6 miles long shortly after leaving Arco. At an earlier time, before the river became incised, it must have flowed at a higher grade at Arco on valley alluvial deposits that have since been removed by erosion (or carried downward on faults) probably during cutting of the gorge. Alluvial fans at the edge of the valley would have then been considerably higher than the present fans. The former height of such old alluvial fans is suggested by inclined facets on mountain spurs above the existing fans; the faceted spurs are erosion surfaces at the upper reaches of the former fans (fig. 8). The present alluvial fans below these faceted spurs, including the fans bounded by the Arco scarp,

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Figure 8.--NEAR HERE.

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are graded to levels more or less close to the valley floor and must date from the closing stages of river entrenchment to present depth. The limiting older date for the start of this entrenchment is, of course, determined by the age of basalt incised by the Big Lost River on the Snake River Plain. This basalt is part of the Snake River Group of late Pleistocene age that occupies most of the eastern Snake River Plain (Malde, 1965). The basalt is not exactly dated, but its time of eruption can be estimated by comparing its weathering with that of other lavas of established age in the region.

Figure 8.--Faceted spurs cut on bedrock above existing alluvial fans along the western flank of the Lost River Range, 9 miles north of Arco, Idaho.

The lava incised by the Big Lost River has well-preserved features of initial surface relief as well as an incomplete thin cover of surficial deposits. In these respects, it resembles basalt at Island Park 90 miles northeast that overlaps the upper part of the Yellowstone Tuff, which is dated by the potassium-argon method at 600,000 years (R. L. Christiansen, U.S. Geol. Survey, personal commun., 1969). In contrast, basalt of the middle Pleistocene Bruneau Formation near Glenns Ferry, Idaho, 120 miles west, which is dated 1.4 million years old (Evernden and others, 1964, sample KA 1188), has no initial surface relief and has been extensively modified by the geologic process of mass wasting (Malde, 1964).

Thus, the alluvial fans near Arco that are displaced by faulting along the Arco scarp date near the end of an episode of valley entrenchment that probably began no more than half a million years ago.

Geophysical evidence

Faulting, however, has been in progress for a long time between a subsiding crustal block represented by the Big Lost River Valley and rising blocks represented by the adjoining mountains. Such faulting has been determined from regional geophysical studies by D. R. Mabey and his associates, U.S. Geological Survey, including detailed observations of gravity, seismic-refraction, and resistivity in a section across the Big Lost River Valley 2 miles north of Arco (fig. 9). In this section, the geophysical measurements indicate that a fault with 1,500 feet

Figure 9.--NEAR HERE.

of aggregate displacement between valley deposits and bedrock of the Lost River Range coincides approximately with the Arco scarp. Other related faults in this section displace Tertiary volcanic rocks. Clearly, the Arco scarp in surficial fan gravel expresses only the latest fault movements that began long ago.

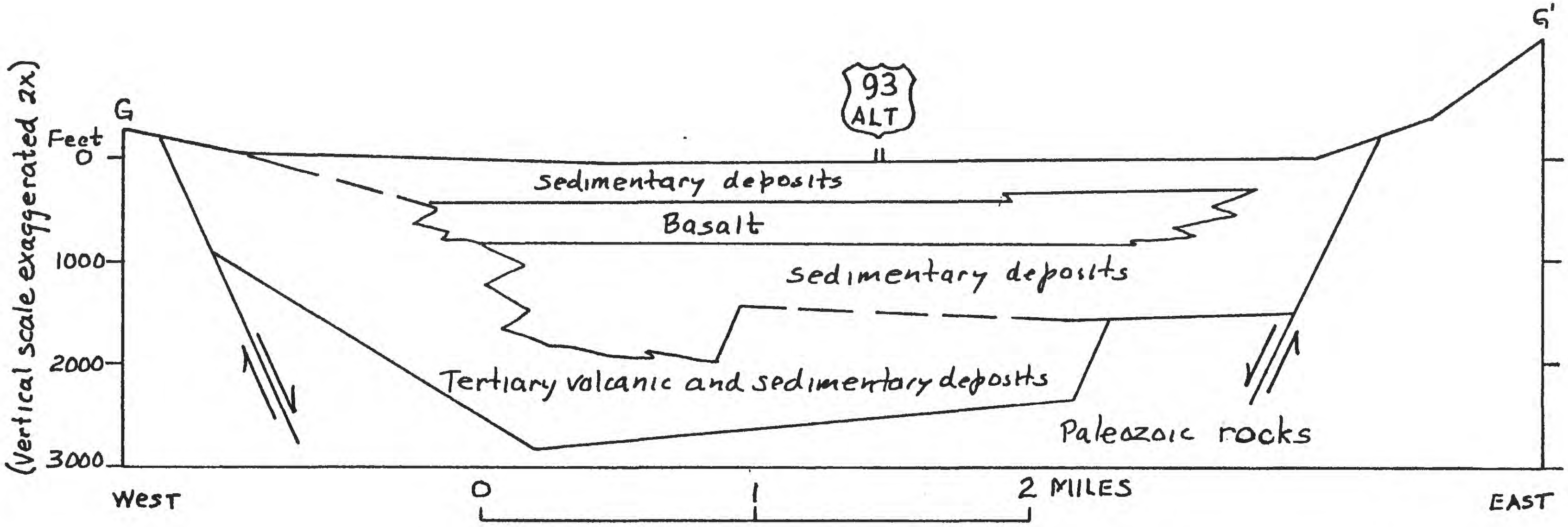

Figure 9.--Generalized geologic cross-section 2 miles north of Arco, Idaho, compiled by D. R. Mabey and associates, U.S. Geological Survey, from gravity, seismic-refraction, and resistivity surveys completed in 1968.

Inferences from landforms

Because a fault at the foot of the Lost River Range has evidently existed for a long time, it is of obvious interest to determine, if possible, the dates of latest faulting on the Arco scarp to better appraise whether movement might again soon resume. Landforms in this area provide some clues.

One curious aspect of the landscape, which may indicate that the area near the Arco scarp is currently subsiding along a fault, is the route of the Big Lost River that here hugs the east side of the valley and erodes the extremities of the alluvial fans. On the opposite side, the alluvial fans merge imperceptibly into the valley floor. A possible explanation for the path taken by the river is that subsidence is gradually tilting the valley floor east, presumably at a rate fast enough to prevent diversion of the river by the westward spread of fan gravel. If so, the existing condition of approximate equilibrium between river erosion and fan building implies that subsidence by faulting is currently active.

On the other hand, a traverse on foot along the Arco scarp shows that none of the young alluvial fans that occupy gaps where the scarp has been breached by streams are themselves visibly offset by faults, and this circumstance implies that faulting is not currently active. Deposition on these young fans apparently occurs slowly and intermittently by local sheets of debris brought down every decade or so by sporadic runoff from storms. Thus, the surfaces of the young fans are probably several hundred years old. While the young fans have been building without noticeable interruption by faulting, the Arco scarp has been slowly eroding to its present subdued slope. Such relations suggest that the last faulting along the scarp is at least several hundred years old, possibly several thousand years old. Certain features of the soils associated with the Arco scarp are compatible with this estimate and indicate probable age limits for times of movement.

Soils at site A-5

At site A-5, one of the places where young alluvial gravel spills from a gap in the Arco scarp (4 miles north of Arco on fig. 2), pits were dug at five places to study the various soil profiles. The soils were examined in company with Jack O. Harwood, a soil scientist with the Soil Conservation Service, U.S. Department of Agriculture, Idaho Falls.

A pit in young alluvial gravel at the gap shows 2 1/2 feet of brown stony loam on open-textured gravel in which a weak carbonate horizon 0.8 foot thick immediately below the loam is expressed by stones thinly coated with calcium carbonate films. Carbonate coatings persist on the undersides of some stones to the pit floor, 6 1/2 feet deep. No conspicuous horizon of clay and oxides is recognizable above the carbonate. By comparison with soils on other alluvial deposits in the Rocky Mountain region, I judge that this soil profile exhibits less weathering than shown by the so-called "Altithermal" or "early Recent" soil on deposits more than 4,000 years old. (For a discussion of the radiocarbon chronology of alluvial deposits and soils, see Haynes, 1968, especially p. 607-608.) If so, the young alluvial gravel is less than 4,000 years old, and the latest faulting along this part of the Arco scarp is correspondingly older.

A second pit in the young alluvium, on the stream floor 300 feet east of the scarp, shows substantially the same soil profile as the first, to a depth of 6 feet. Perched about 4 feet above the stream floor at this place is a small terrace remnant of alluvial gravel preserved from an earlier time of stream deposition. A pit in this terrace shows that the surface stony loam is only about a foot thick but that the carbonate horizon is virtually identical with carbonate in the other pits. Loam seems to have been partly stripped from this terrace, but the weathering profile suggests an age not much older than that of the young gravel along the present stream.

Some 18 feet higher than the terrace remnant, at the surface of the high alluvial fan marked by the Arco scarp, the soil is much more calcareous. The surface is stony, and many of the stones are crusted with carbonate. A pit shows 1 1/2 feet of calcareous and slightly clayey stony loam on a caliche horizon 2 1/2 feet thick in which carbonate-encrusted stones are more or less firmly held by a matrix of carbonate-impregnated silt (hardpan). Caliche coatings are present on the undersides of stones to the pit floor, 6 1/2 feet deep, and a friable silt matrix at this depth effervesces violently with acid. I estimate that the thickness and abundance of carbonate in this soil profile resembles that of the carbonate horizon in soils of this region that have formed on deposits about 30,000 years old, notably the soil on gravel deposited by the Bonneville Flood (Malde, 1968, p. 11), and the soil on outwash associated with a Bull Lake moraine in Lemhi County (Gallup, 1962).

The fifth pit, 7 1/2 feet deep at the toe of the Arco scarp, shows a greatly augmented thickness of surface loam, 4 1/2 feet, in vaguely defined layers that dip away from the scarp face. This loam evidently accumulates at the scarp toe after being washed from the fan surface and the scarp above. A carbonate horizon under the loam resembles carbonate in young alluvium at the first three pits. It is noteworthy that the strongly calcareous soil above the scarp, which might have been dropped down at the toe by faulting, is not exposed in this pit.

The various soil profiles investigated at site A-5 suggest that the Arco scarp is a rather old feature of the landscape. The scarp is formed in alluvial gravel probably older than 30,000 years, and faulting along this part of the scarp apparently has not involved alluvial deposits of the last 4,000 years. Calcareous soils associated with the faults found at site A-2 permit further deductions about the time of faulting.

Soils at site A-2

As at site A-5, the alluvial fan at the head of the Arco scarp at site A-2 has a strong caliche soil of the kind found in this region on deposits 30,000 years old, or older. This caliche soil, however, is younger than the oldest recognizable faulting of the fan gravel, as shown by measurement of the minimum aggregate vertical offset--at least 40 feet (p. 21). If the original position of beds is restored this minimum amount, the initial gravel surface west of the fault zone (that is, the horizontal contact 12 feet below survey mark 9) would be above the projected grade of the caliche soil east of the faults. The caliche therefore formed after erosion had stripped some gravel from the elevated fan east of the fault. Assuming that the time of formation of the caliche soil on this erosion surface is more or less accurately known, the episode of faulting that preceded erosion of this fan gravel is more than 30,000 years old.

When caliche formed on fan gravel at the present head of the Arco scarp, it seems likely that caliche would have also formed on colluvium west of the fault scarp of that time. The comparatively thick zone of caliche on colluvium and fault rubble near survey mark 9 is probably the roots of such a caliche soil. Exposures along the trench obviously do not establish this correlation, and interpretation is further hampered by partial erosion of the soil profile at survey mark 9, but I judge that the thickness and abundance of caliche on the colluvium and fault rubble are comparable to these aspects of caliche in soils of this region 30,000 years old. In contrast, moderately calcareous soil that has formed on alluvial gravel in a terrace 25 feet above the Snake River from Idaho Falls to Blackfoot, which dates about 10,000 years, has only diffuse caliche in a carbonate horizon a foot or two thick. (For a review of soils applied to stratigraphic studies of surficial deposits in the Western States, see Morrison, 1967.)

Ages based on comparisons of soils in this region, however, must be hedged with doubt, especially because soils along the Arco scarp have been studied thus far only at a few places. Moreover, fan gravel cut by the Arco scarp has a large component of limestone, and the role of this ingredient as a possible factor in producing carbonate soil horizons of augmented thickness and intensity is virtually unknown. In short, the caliche soil in the fault rubble and colluvium might be considerably younger than 30,000 years, even perhaps as young as 10,000 years.

Thus, assuming that the caliche soil at survey mark 9 is at best only approximately dated, faulting on the west branch of fault A (where the caliche soil is not offset) could have occurred more than 30,000 years ago, but the faulting could also have happened as recently as about 10,000 years ago.

As previously mentioned (p. 27), the caliche soil at survey mark 9 terminates abruptly against the wedge of fault rubble at survey mark 10, probably because of faulting. If so, this movement took place in the last 30,000 years, perhaps in the last 10,000 years.

Finally, the Arco scarp at site A-2 is mantled by surficial slope deposits 2-4 feet thick in which no sign of renewed offset on the faults can be seen. These slope deposits support only an immature soil that expresses weathering no greater than that seen in the young deposits at site A-5. By this comparison, the slope deposits at site A-2 are less than 4,000 years old. Movement on the faults is correspondingly older.

Summary

Faulting in alluvial fans younger than half a million years old along a 10-mile stretch at the foot of the Lost River Range north of Arco began more than 30,000 years ago and formed the rather continuous step known as the Arco scarp. Faulting of fan gravel at site A-2, about 6 miles north of Arco, resulted in an aggregate vertical displacement of more than 40 feet. At least one episode of movement at this site caused a minimum vertical offset of 15-20 feet, and a subsequent offset was more than 10 feet. These displacements most probably occurred more than 30,000 years ago, to judge from an incomplete profile of caliche soil that was apparently involved in the faulting, but uncertainties in the interpretation of this evidence permit the possibility of faulting perhaps more recently than 10,000 years ago. Nonetheless, surficial deposits of the last 4,000 years, which have only immature soils, are not visibly broken along the scarp. Even this observation, however, does not rule out very recent faulting; the peculiar course of the nearby Big Lost River may be a consequence of eastward tilting by contemporary subsidence on a fault in the area of the Arco scarp.

Howe scarp

General features

The Howe scarp is an intermittent step of variable height along the upper reach of alluvial fans that descend westward from the Lemhi Range to the Little Lost River north of Howe (fig. 10). Like the Arco scarp,

Figure 10.--NEAR HERE.

the slope along the Howe scarp varies between 20° and 25°, whereas slopes on the adjoining fans are no steeper than 8°. The scarp is therefore conspicuous as a more or less linear discontinuity in slope. The Howe scarp rather accurately follows the irregular outline of the Lemhi Range, although the distance from outcropping bedrock widens on the south to about 1/2 mile. The Howe scarp has two parts, a northern segment 4 miles long centered on North Creek, and a southern segment 9 miles long centered approximately on Black Canyon[/]. Although scarplike features are found in a hilly area of bedrock between these segments, these two parts of the Howe scarp could have formed at different times. As discussed below, excavation midway along the length of the southern segment shows that this part of the Howe scarp coincides with several closely spaced high-angle faults that moved at different times. The northern segment of the Howe scarp, which has similar surface characteristics, also almost surely formed as a consequence of faulting.

[/]The name Black Canyon is applied on current maps to the westernmost of three canyons seen from Howe on the southwest-facing flank of the Lemhi Range. It debouches in sec. 3, T. 6 N., R. 29 E. This canyon is also known locally as "West Canyon."

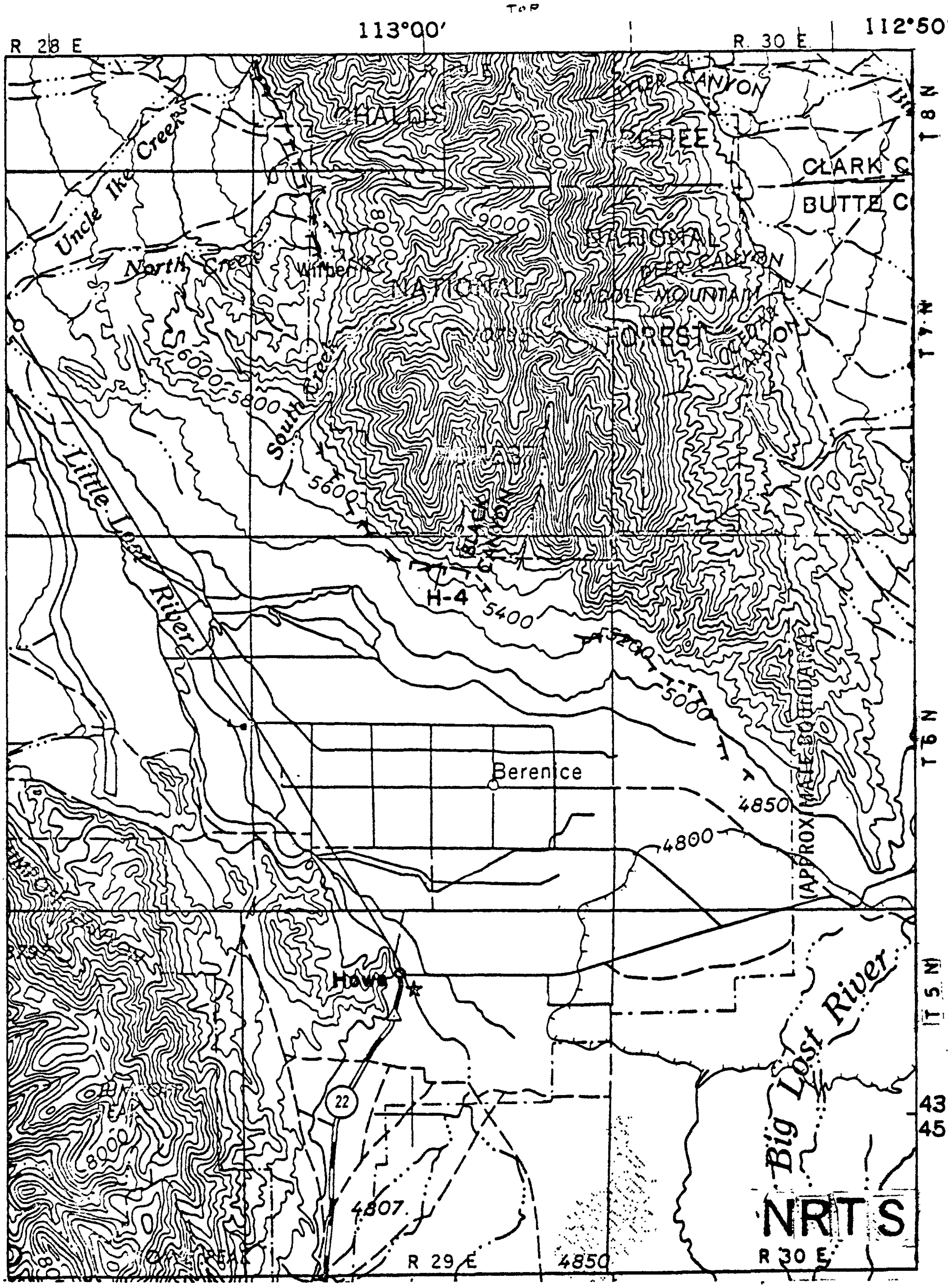

Figure 10.--Map of Howe scarp in alluvial fans north of Howe, Idaho, showing location of site H-4 discussed in the text. A gap in the scarp line between North Creek and South Creek is occupied by a bedrock ridge. A gap north of Berenice is formed by a broad alluvial fan younger than the scarp. Shorter gaps elsewhere along the scarp line are also filled by young fans.

Because the Howe scarp is interrupted at many places by gaps occupied by young alluvial deposits, neither of the two principal segments is entirely continuous. Moreover, the height and length of these many individual parts are rather irregular, especially in contrast with the general uniformity of the Arco scarp. The scarp height varies from a faintly recognizable step in the SE 1/4 sec. 3, T. 6 N., R. 29 E., to more than 40 feet in several places. Substantially continuous stretches of the scarp range from 300 feet to more than 1/2 mile long. The scarp-free gaps are commonly from 300 feet to more than 500 feet wide (considerably more than along the Arco scarp), and one gap north of Berenice is 1 1/2 miles across. Such differences in height and length along the Howe scarp are, of course, partly a consequence of local differences in the interplay of erosion and deposition, which in time tend either to subdue or conceal former topography, but the variable height and length also may be partly due to intermittent movement on faults that displace the alluvial fans (see p. 70-73).

The differences in soils, vegetation, and dissection by gullies observed in alluvial fans above and below the Arco scarp are also found along the Howe scarp, and in similar ways these differences indicate that the Howe scarp forms a general boundary between older fans cut by the scarp and younger fans that interrupt its continuity. Times of faulting along the Howe scarp, as discussed at the close of this chapter, therefore can be appraised from the ages of these alluvial fans.

Faulting at site H-4

Selection of site

A clearly defined stretch of the Howe scarp at the front of a high alluvial fan about midway along the Black Canyon segment (site H-4, about 7 miles north of Howe, near the center of sec. 3, T. 6 N., R. 29 E.; see fig. 10) was selected for detailed study, partly because a large backhoe could be maneuvered to a digging position at the head of the scarp, and partly because the variable height of the scarp nearby is representative of the appearance of the Howe scarp at most places along its length. Figure 11 is a vertical aerial photograph of the area of site H-4, and Figure 12 is a view from ground level. The Howe scarp

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Figure 11.--NEAR HERE.

Figure 12.--NEAR HERE.

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at site H-4 is 500 feet from the nearest bedrock outcrops at the foot of the Lemhi Range. Bedrock in this part of the Lemhi Range consists of quartzite and limestone formations that strike north, perpendicular to the local trend of the Howe scarp (Ross, 1961, pl. 7). The fan gravel at site H-4, however, is composed almost entirely of fragments of quartzite.

Figure 11.--Vertical view of Howe scarp in sec. 3, T. 6 N., R. 29 E., showing location of site H-4 in alluvial fan. The stream debouching from Black Canyon on the left (west) is building an alluvial fan younger than the Howe scarp. (Enlarged from U.S. Department of Agriculture aerial photograph CVP-11W-47 taken August 23, 1959.)

Figure 12.--View northeast toward Howe scarp in SE 1/4 sec. 3, T. 6 N., R. 29 E., which is 1 1/4 miles distant. Segments of the scarp at the right and left are separated by a gap occupied by an alluvial fan younger than the scarp. Site H-4 is in the middle of the left-hand segment.

A secondary factor in selecting site H-4 for excavation is the presence of a flattened bench that extends 300 feet south from the toe of the scarp to an abrupt parallel boundary at the head of a lower alluvial fan. This bench perhaps conceals a gravity graben--that is, a trough between two opposing high-angle faults--and it was anticipated that a trench at the scarp could be continued across the bench to investigate its internal features. As matters turned out, the excavating equipment was needed for other work when excavation at the scarp was completed, and no observations have yet been made in the bench at the scarp toe.

A trench 25-30 feet deep and 400 feet long was excavated at site H-4 perpendicular to the Howe scarp, thus exposing beds of fan gravel interrupted by high-angle faults in the middle of the scarp face (fig. 13). As in the sketch made at Arco site A-2, the profile drawn

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Figure 13.--NEAR HERE.

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at site H-4 emphasizes distinctive beds that can be reliably traced, especially beds that are useful for measuring displacements on the faults. Where the direction of fault movement can be determined at site H-4, fault blocks toward the scarp toe moved relatively down (as might be expected), and it seems likely that this sense of movement applies also to the faults of indeterminate displacement.

The scarp height at site H-4 is 45 feet if allowance is made for local slope of alluvial fans. More typically, the height of the Howe scarp is only 15-20 feet. The greater height at site H-4 might therefore suggest that displacement on faults at this place is uncommonly large and therefore misleading in predicting displacement at sites where the apparent scarp height is small. However, several factors make the scarp height at any locality an untrustworthy indicator of fault displacement, even though the height undoubtedly measures a minimum aggregate displacement. For example, erosion above the scarp, deposition of colluvium at the toe, and overlap by adjacent younger fan deposits are all factors that tend to reduce the scarp height and obscure the evidence of fault displacement. Thus, in the absence of detailed study at several sites along the Howe scarp, it would be groundless to assume that the scarp height at H-4 is misleading evidence of locally excessive fault displacement. That is, displacement of similar magnitude might be found by excavating on the Howe scarp where geologic processes have reduced the scarp height. For instance, in the distance 600 feet east from site H-4, the scarp decreases in height and disappears for a short stretch by reason of overlap by younger alluvial deposits, but it is unlikely that the faults which account for the scarp could similarly decrease abruptly in displacement; faults are ordinarily several thousand times longer than their displacement. I therefore conclude that site H-4 is likely to be as typical as any other site that could be selected for detailed study along the Howe scarp.

Geologic relations of faults

For convenience of discussion, the fault planes recognized at site H-4 are designated by letters. Several of these faults displace coherent sequences of bedded gravel and are well-defined planes generally no wider than a single pebble in cross section. Some of the identified faults, however, are better described as abrupt boundaries of fault rubble against bedded gravel--for instance, faults E and F. At such zones of fault rubble the initial faulting probably was by simultaneous displacement at both boundaries, thus producing the rubble, but later movement may have occurred in lesser amount only at a single boundary of the rubble. The straightness of the fault planes at site H-4 suggests that the dominant component of movement on these faults was vertical, indeterminate components of strike-slip movement cannot be ruled out. Because of the complexities caused by multiple episodes of movement on the numerous faults encountered at site H-4, the various geologic features will first be described in sequence proceeding upslope. The significance of these features in estimating aggregate displacement, episodes of movement, and age of faulting is interpreted in subsequent sections.

At the toe of the scarp at site H-4 a mantle of slope deposits (pebbly sand) 2-3 feet thick buries colluvium and eolian deposits that include remnants of a weak caliche soil, 4 feet below the surface (see the units identified in fig. 13). This soil continues intermittently upslope to survey mark 19. At a depth 9 feet below survey mark 3, the colluvium rests abruptly on a compact layer of strong caliche (lower buried caliche), which represents a soil that originally formed on the old ground surface directly on gravel of the alluvial fan. This gravel, a thick-bedded unit of angular pebbles and some layers of angular cobbles, when examined to the trench floor, has no other signs of buried soils. The gravel beds dip about 7° south. The lower buried caliche on the gravel is easily traceable upslope conformably to bedding. Near survey mark 6, this caliche is overlapped by another strong caliche soil of similar appearance (upper buried caliche), and both soils then continue together upslope. Between these soils is a thin layer of sand, pebbles, and cobbles. Below the caliche soils, at a depth of 14 feet between survey marks 5 and 13, is a distinctive layer of open-textured cobble gravel partly impregnated with carbonate material that was precipitated from ground water.

The first break encountered in continuity of the fan gravel, fault A, offsets a readily identified graded bed of angular pebbles a vertical distance of 8 feet. In approaching fault A, the lower buried caliche decreases in prominence, but it also is evidently interrupted by the fault. The upper buried caliche continues across fault A, and the characteristic textural aspects of the fault appear to be faintly expressed in deposits in which this caliche was formed. Farther upslope, beginning at survey mark 15, the upper buried caliche becomes distinctly platy, and it is properly described as hardpan.

Fault B is visible at the trench floor. It displaced bedded gravel on the south against fault rubble, perhaps in company with movement on fault C, but the amount and direction of offset are indeterminate. Although fault B is clearly defined in the lower part of the trench, it does not disrupt the persistent upper buried caliche at the top of the gravel.

Faults C and D together define the limits of a rubble zone 5 feet wide in which tabular pebbles in the lower part are mostly arranged on edge more or less parallel to the faults. The rubble fabric is more random in the upper part. It is curious that the dip on these faults, 64°, matches the dip of faults at Arco site A-2. Fault C, like the upper reach of fault A, is vaguely discernible in the upper buried caliche, as expressed by material that crumbles relatively easily from the trench face, but this fault does not displace the caliche. The amount and direction of offset on fault C are unknown. Fault D, however, clearly terminates the upslope extent of this strong caliche, evidently by a relative downward displacement of the block on the south. This direction of movement is indicated by a triangular wedge of the upper buried caliche immediately south of the upper part of fault D; the wedge is surely a "sliver" that lodged against the fault when the block on the south was dragged down by faulting. The upper reach of fault D, 2 feet below the surface, also coincides with the downslope end of a moderate caliche soil, which is less well developed than the buried caliche soils south of faults A and D, but which is nonetheless thicker, more calcareous, and more persistent than the weak caliche near the surface downslope. Unfortunately, this terminus of the moderate caliche also approximately coincides with a cross-cutting contact at the base of young colluvium (pebbles and sand) on the triangular wedge of upper buried caliche--see relations sketched at survey mark 20--and evidence for the abrupt end of the moderate caliche is ambiguous. The problem of determining possible faulting of the moderate caliche is discussed later (p. 76-78). The young colluvium at survey mark 20 thickens downslope beneath a thin mantle of slope deposits, and it locally has the weak caliche soil in its upper part.

A careful search immediately after the excavation of site H-4 was completed (June 19-22, 1969) failed to identify any bed north of fault D that matches a bed on the south. The total displacement on fault D is therefore indeterminate. Deposits adjacent to fault D on the north represent two kinds of material, bedded gravel in the lower part, and mixed debris of old colluvium in the upper part (that is, the upper 10 feet of deposits at survey mark 21), both being sharply cut by the fault. Clearly, one offset on fault D amounted to more than 10 feet, which is the preserved thickness of the old colluvium. The old colluvium in turn covers the eroded upper reach of a zone of fault rubble bounded by faults E and F. This rubble zone is nearly 2 feet wide, even though the vertical displacement shared by faults E and F is only 4 feet, as measured by offset of a sequence of several distinctive beds. By this evidence, the width of a rubble zone could be regarded as being quite unrelated to the amount of fault displacement, whereas many other observations favor a more or less direct ratio between fault width and distance of offset. Faults such as E and F, however, in which the fault plane passes above the block that moved relatively down, are known as "reverse faults". Separation of fault blocks here by vertical displacement in a zone of reverse faulting therefore may account for the curiously exaggerated width of rubble between faults E and F.

Continuing north from fault F, an unmistakable pair of gravel layers near the top of the section, namely a graded pebble layer 1 1/2 feet below a layer of angular cobbles, indicates 1 foot of vertical offset on fault G. This fault is exceptionally well-defined and straight, being only an inch or two wide. Fault G is truncated at the top by a thin surficial layer in which the moderate caliche soil previously noted at fault D is formed.

Beginning close to fault G, a conspicuous bed of open-textured angular pebbles 10 feet below survey mark 23 persists upslope beyond faults H and I. This layer, together with one of the gravel layers above, demonstrates 4 feet of vertical displacement in a disrupted zone embraced by the upper part of faults H and I. At greater depth, gravel between these faults is preserved in a bedded sequence, and matching beds indicate 1 foot of vertical offset on fault H and 3 feet of offset on fault I. Fault H dips noticeably less steeply than the other faults. Fault I makes a comparatively irregular trace in the trench wall, but such irregularity may be a result of variable resistance to movement in adjacent gravel beds of contrasting texture. Like the other fault planes, faults H and I do not reach the present ground surface. They are recognizable, however, 1 1/2 feet below the surface, where they are truncated by the moderate caliche.

The fan gravel upslope from fault I is exposed along the trench to the head of the Howe scarp. No other faults are visible. It is noteworthy that this fan gravel, in common with gravel elsewhere along the trench, is conspicuously silty. H. H. Waldron, during a field conference on June 18, 1969, suggested that the silt probably was brought by southwesterly winds from the Lost River playas while fan gravel was accumulating by occasional local runoff. The gravel bedding is lenticular, but several beds can be traced far enough to measure a consistent initial dip of 7° south, which is virtually identical to the dip of beds beyond the fault zone. Thus, movement on the faults did not differentially rotate fan gravel at the head and toe of the scarp.

Finally, upslope from survey mark 42, a strong caliche hardpan at the surface closely resembles the two buried caliche soils that extend from the scarp toe to faults A and D, respectively. This strong caliche conforms with the alluvial fan above the scarp and is being eroded by gradual headward retreat of the scarp.

Aggregate displacement at site H-4

The total offset on the various faults of known displacement at site H-4 amounts to 17 feet (8 feet at fault A, 4 at E and F, 1 foot at G, and 4 at H and I). To this can be added at least 10 feet of vertical displacement on fault D, which resulted in the upper buried caliche being placed against the old colluvium. A minimum measurable offset of 27 feet is thereby obtained. The aggregate displacement, although indeterminate from geology exposed along the present trench, cannot be less than the scarp height (45 feet) if movement on all the faults was relatively down toward the scarp toe. Further, for a closer estimate of minimum vertical offset, the scarp height should be augmented by the depth to the lower buried caliche on fan gravel at the scarp toe, and this addition yields an aggregate displacement of more than 50 feet. As at Arco site A-2, some original fan gravel above the scarp has surely been lost by erosion with the passage of time, and the total offset therefore might be much more than 50 feet. The excess displacement over the 27 feet of measurable offset is obviously represented by movement shared between faults B, C, and D.

Fault sequence at site H-4

The details of faulting visible in the trench at site H-4 require several episodes of movement to account for the arrangement of various blocks of gravel and fault rubble. Despite an appearance of complexity, the geology provides unquestionable evidence of relative movement between several neighboring faults and thereby establishes partial sequences of multiple displacement. The relative times of movement on other faults that are far apart, although less certain, can be interpreted from a knowledge of geologic processes. By deciphering the partial sequences of episodes of faulting, and by considering overlap of geologic events identified in these sequences, a composite record of faulting at site H-4 can be deduced. This composite sequence, as summarized below, includes at least five episodes of faulting. Some of the geologic relations from which this sequence is derived also pertain to the probable ages of faulting, and this problem will be discussed shortly.

The partial sequences of features related to faulting at site H-4 are listed in table 1. The first two sequences are derived from direct objective evidence. The third sequence is deduced from indirect evidence. The features listed here have been partly explained on previous pages, and their geologic relations are further elaborated in the discussion that follows.

Table 1.--*Sequences of geologic features related to faulting at site H-4*

Feature	Relation to other nearby feature
Sequence 1	
Weak caliche---------------------	Formed on young colluvium
Young colluvium------------------	Derived from scarp at fault D
Fault D--------------------------	Displaced upper buried caliche
Upper buried caliche-------------	Formed on buried scarp
Buried scarp---------------------	Truncates faults A, B, and C
Fault A--------------------------	Displaced lower buried caliche
Lower buried caliche-------------	Formed on fan gravel
Sequence 2	
Fault D--------------------------	Displaced old colluvium
Old colluvium--------------------	Deposited on faults E and F
Sequence 3	
Faults B and C-------------------	Locally changed old colluvium to fault rubble
Old colluvium--------------------	Derived from scarps at faults G, H, and I

The relative ages of features enumerated in the first sequence are conveniently discussed in ascending order. The lower buried caliche on fan gravel almost surely marked the initial surface of the alluvial fan that was cut by displacement on fault A. Before or after movement on fault A, or concurrently, displacements occurred on faults B and C. (Multiple offsets on faults B and C are likely but problematical.) Erosion of the elevated fan gravel north of fault A then formed a subdued scarp virtually identical in slope with the present Howe scarp. Erosion of the scarp culminated in development of the upper buried caliche, which was in turn truncated by movement on fault D. (The wide rubble zone at fault D, which is older than the upper buried caliche, suggests considerable earlier movement on this fault.) Young colluvium on the upper buried caliche apparently incorporated debris partly derived from the scarp that was created by displacement on fault D. The formation of a weak caliche soil near the present surface completed this sequence.

Features of the second sequence, which have been pointed out in previous remarks (p. 58), are also entirely straight forward. The old colluvium at survey mark 21 rests on the truncated edges of faults E and F, and it is cut by fault D.

The third sequence has been reconstructed as one hypothesis to explain certain relations among deposits that are otherwise hard to understand. These relations hinge on the old colluvium and its involvement in faulting. The old colluvium consists of mixed debris of small and large sizes unconformable on the fan gravel. The only probable source for this debris was a fault scarp upslope, and the old colluvium is accordingly interpreted to be younger than faults G, H, and I. Relatively early movement on these faults is also suggested by a general lack of colluvial debris downslope from their scarps (except the small amount preserved as the old colluvium) and by the further absence of the scarps themselves. In short, topographic steps that were surely created by displacements on faults G, H, and I have been obliterated by gradual slope retreat. The other part of the third sequence concerns the geology downslope from fault D, where the old colluvium is mysteriously unrecognizable. Under ordinary events, if the old colluvium had been dropped down by a displacement on fault D, it would be expected to appear somewhere below the upper buried caliche--for instance, 15 feet below survey mark 17. The absence of identifiable old colluvium in this part of the profile could be a consequence of movement on faults B and C, a process that could have converted colluvium in this vicinity into fault rubble, thus permitting subsequent movement on fault D to place rubble against the existing old colluvium. If so, faults B and C are younger than the old colluvium.

These three sequences, when combined, allow some latitude in assembling a composite record of faulting. One combined sequence is suggested in table 2.

Table 2.--*Composite sequence of features pertaining to faulting at site H-4, and amounts of offset*

[Features listed in order of increasing age]

Feature	*Vertical offset of faults (feet)*
Weak caliche-------------	------
Young colluvium----------	------
Fault D------------------	More than 10
Upper buried caliche-----	------
Buried scarp-------------	------
Faults B and C-----------	Not determined
Old colluvium------------	------
Faults G, H, and I-------	5
Faults E and F-----------	4
Fault A------------------	8
Lower buried caliche-----	-------
Fan gravel---------------	-------

This composite sequence is, of course, subject to several uncertainties, in addition to the unprovable premises about the role of the old colluvium in faulting. An obvious weak link is the relative age of fault A, which could be younger than faults B and C--or any intermediate age. However, movement on either fault B or fault C, prior to the displacement on fault A, probably would have produced colluvial debris that is not identifiable in the profile. In short, the displacement on fault A appears to be an early event. Also, as noted above, at least one early episode of movement on fault D, probably combined with movement on fault C, is demonstrated by the wide zone of intervening rubble, which is capped by the upper buried caliche. Such an early displacement on fault D may account for a considerable part of the observed scarp height at site H-4. Still another factor that remains problematical in analyzing the fault sequence is that several of the faults could have moved either simultaneously or individually.

Notwithstanding the problems that remain in determining the fault sequence at site H-4, several times of faulting are evident. The available data suggest at least five episodes of movement. Together, these displacements resulted in 27 feet of measurable vertical offset and a total displacement of more than 50 feet, as indicated by the scarp height.

Age of faulting

Regional relations

The alluvial fans that spread outward from mountain canyons at the foot of the Lemhi Range near Howe grade almost imperceptibly into alluvium carried by the Little Lost River on the valley floor, and the fans are therefore comparatively young features of the landscape. As traced headward, the fans form an intricate group of adjacent and overlapping deposits, which are expressed as variably gullied surfaces at contrasting heights. The topographic relief between neighboring fans is seldom more than 30 feet. From such differences among adjoining fans, sequences of fan building can be generally deciphered in local areas. Thus, although some active (modern) fans are in the process of covering stable (relic) fans, it is clear that the spread of fan gravel toward the valley ordinarily has been accompanied by headward erosion so that most older fans stand as high erosional remnants near the mountain front. It is the higher, apparently older, alluvial fans that are marked by the Howe scarp. Such fans are perched several tens of feet above the principal streams at canyon mouths. The Howe scarp, as a step in the higher fans, therefore resembles the Arco scarp in the regional landscape, and other topographic aspects of alluvial fans near Howe and Arco are also similar. Probably the fans of both areas embrace approximately the same range in age.

Well records show that the fan gravel near Howe spreads southward over basalt of the Snake River Plain at the Lost River sinks, where the gravel grades in places into lakebeds.. A few layers of such sediment are also interbedded with the basalt and indicate "deposition along channels and shallow short-lived lakes overrun by spreading lava" (Walker, 1964, p. E16, pl. 2, section C-C'). Evidently, the fan gravel is mostly younger than the basalt. Like the basalt southeast of Arco, this lava has well-preserved surface features that formed during its eruption, and it similarly lacks conspicuous signs of prolonged mass-wasting. Thus, the exposed lavas near Arco and Howe are probably not greatly different in age--about half a million years old, or less, according to the evidence previously explained (p. 31). The deposits of fan gravel that overlap the basalt are surely considerably younger. By this argument the Howe scarp expresses faulting in deposits less than half a million years old.

Inferences from landforms

One of the geologically interesting aspects of the Howe scarp is its variability in height in short distances (p. 46). At such places, a traverse on foot along the scarp generally shows that changes in scarp height correspond with changes that accompany a transition from one alluvial fan to another. An instructive example is the stretch of the Howe scarp that extends 1/2 mile southeast from site H-4 (from the center to the southeast corner of sec. 3, T. 6 N., R. 29 E.). From a height of 45 feet in fan gravel contiguous to Black Canyon at site H-4, the scarp abruptly diminishes to a faintly discernible trace on the surface of a neighboring fan derived from Middle Canyon (sec. 2, T. 6 N., R. 29 E.).

If it were possible to determine actual differences in age between such adjacent fans, the differences in scarp height could then be equated with differences in aggregate displacement that resulted from intermittent movements that accumulated during differing lengths of time. Although an equation of this kind might be theoretically sound--a high scarp representing the sum of numerous offsets of an old fan, and conversely, except as modified by surficial geologic processes that tend to obscure the scarp (p. 52)--such an equation would be impractical to apply, if only because the various fans interrupted by the Howe scarp cannot yet be dated in absolute years. Even attempts at distinguishing relative ages between neighboring fans inevitably relies on contrasts in landforms whose interpretation may be debatable. A chronological scheme for the alluvial fans near Howe would require detailed study at various places along the mountain front--a study analogous to that exemplified by a recent analysis of alluvial fans in Death Valley (Denny, 1965)--but such a study is beyond the scope of this investigation.

Nonetheless, from a traverse along the length of the Howe scarp, many examples can be found in which differences in scarp height on adjoining fans appear to be partly a function of differences in age. The higher scarps, for instance, occur only at fans that are the older local units. Also, the fans that are not broken by the Howe scarp are clearly young features of the landscape. Many of these young fans spill from canyon mouths entrenched at least a few feet below the high fans, such as the young fan at East Canyon (sec. 1, T. 6 N., R. 29 E.). A few cover older fans by spilling from a canyon not yet entrenched, such as the young fan at the mouth of Black Canyon that abruptly terminates the north end of the scarp segment at site H-4. Like the similar young fans near Arco, these fans probably are less than 4,000 years old, and the latest faulting on the Howe scarp is correspondingly older. Exceptionally low scarps at fans that are undoubtedly relatively old, however, are not hard to find. To continue with the example with which these remarks began, the fan of Middle Canyon marked by a faint scarp is incised along Middle Canyon Creek by a valley 33 feet deep and 400 feet wide. Such dissection obviously demonstrates that the Middle Canyon fan is older than nearby fans that are less dissected. Despite exceptions of this kind, the significant general conclusion is that intermittent movements expressed by differences in scarp height appear to have occurred throughout the length of the Howe scarp, including apparent displacements of a few feet on fans that are topographically low, comparatively little dissected, and therefore relatively young. The landforms in alluvial fans therefore reinforce the evidence of intermittent movement on the Howe scarp found at site H-4, but the landforms visibly involved in faulting do not include the young alluvial fans of the last 4,000 years.

Soils at site H-4

The relations of buried soils to the faults at site H-4, which are summarized below, indicate episodes of movement more or less in harmony with times of displacement deduced at Arco site A-2, namely various offsets older than 30,000 years, followed by movement younger than 30,000 years, perhaps even younger than 10,000 years, and possibly still active in the last 4,000 years. As at Arco, however, interpretation of the soils at site H-4 is hampered by past and present erosion so that comparisons with other soils depend on the properties of caliche that formed initially at some depth in the soil profile. That is, the original surface horizons of clay and oxides, which could otherwise be used to reinforce the correlations of the buried soils, have been removed. The ages of faulting that are thus derived solely from characteristics of residual caliche layers can only be regarded as approximate. Nevertheless, correlations based on such relic soils are the most direct evidence available for dating times of faulting on the Howe scarp.

Strong caliche on the fan surface at the head of the Howe scarp at site H-4 closely resembles caliche above the Arco scarp and matches caliche soils elsewhere in this region on deposits that are 30,000 years old, or older (p. 38). By this comparison, the fan gravel broken by the Howe scarp is at least 30,000 years old.

The lower buried caliche on fan gravel concealed at the foot of the Howe scarp, south of fault A, is analogous in thickness and intensity to the strong caliche above the scarp (although a former link between these soils is improbable because the high fan has been comparatively more vulnerable to erosion). The presence of the lower buried caliche therefore suggests that the fan gravel below is also at least 30,000 years old. After displacements on faults A, B, and C, and probably after early movement on fault D as well, together with various offsets on faults E, F, G, H, and I, according to the sequence of faulting previously explained, a subdued scarp was formed, and another strong caliche soil (the upper buried caliche) developed on the scarp of that time. The upper buried caliche is virtually identical to the lower buried caliche. By the standards of thickness and intensity of carbonate used for comparison with other relic soils of the region, the upper buried caliche therefore also dates no later than about 30,000 years ago.

The profile exposed at site H-4 thus includes three layers of caliche hardpan, substantially identical in appearance, which are estimated to be not less than about 30,000 years old, even though these soils surely formed at different times. The actual duration spanned by formation of these soils, including the intervening episodes of faulting and erosion, cannot be further estimated from the available evidence. It appears, however, that movements on all the faults, perhaps in aggregate comprising the major amount of displacement that formed the Howe scarp, occurred during this early period.

Movement on fault D after formation of the upper buried caliche probably occurred in the last 30,000 years, according to the date assigned to this caliche hardpan. A closer estimate of the time of displacement, however, is confused by the ambiguous relation of fault D to the downslope terminus of the moderate caliche soil, which coincides with the fault, but which also coincides with the upslope reach of a layer of colluvium younger than the fault (see fig. 14 and p. 56). The

Figure 14.--NEAR HERE.

distribution and abundance of carbonate in the moderate caliche resembles these aspects of carbonate horizons in soils of this region found on deposits about 10,000 years old, such as soil on the 25-foot terrace along the Snake River between Idaho Falls and Blackfoot (p. 40), and the soil profile on Pinedale outwash in Lemhi County described by Gallup (1962). If the moderate caliche is indeed cut by fault D, this displacement would be accordingly dated as not older than 10,000 years. However, the terminus of the moderate caliche at the fault might be nothing more than an unusual coincidence. No equivalent caliche is identifiable in the block that presumably moved relatively down, namely the south block where preservation of a former soil would be expected--as, for example, is shown by burial of the lower buried caliche south of fault A. If the moderate caliche is thereby oppositely interpreted as a soil that truncates fault D, the last displacement would be correspondingly dated as not younger than 10,000 years. The relation of the moderate caliche to the adjacent young colluvium, if this can be determined, is of obvious importance in deciding between these alternatives.

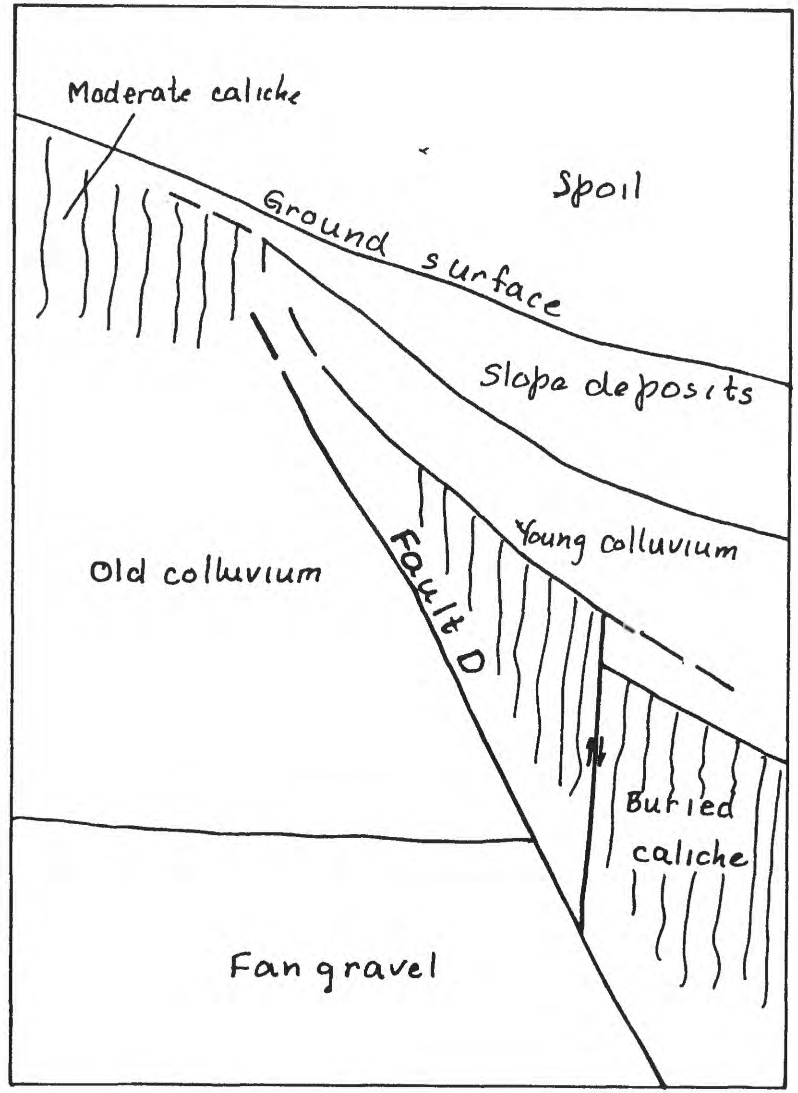

Figure 14.--Photograph of upper 13 feet of trench wall of site H-4 at upper reach of fault D near survey mark 20. Significant features visible in the photograph are indicated on the accompanying diagram. The perspective of this view is slightly distorted by use of a wide-angle lens inclined downward.

The young colluvium encroaches on the moderate caliche along a steeply inclined contact (see relations at survey mark 20) and appears to be entirely younger than the caliche. The projected base of the young colluvium also coincides with the projected plane of fault D, and it seems evident that the colluvium incorporates debris that fell from a scarp formed by an offset on the fault. Such an offset would have cut the moderate caliche, unless the young colluvium is a double unit composed of mixed slope deposits of two ages: material approximately contemporaneous with a displacement on fault D (but older than the moderate caliche); and material younger than fault D, which accumulated after the eroded upper reach of the fault had been healed by development of the moderate caliche soil.

The relative age of fault D to the moderate caliche is therefore equivocal and cannot be satisfactorily deduced from the available field evidence. This problem of course pertains only to the matter of dating the last movement on fault D, and the observation that a displacement on fault D is the latest recognizable offset at site H-4 remains unaltered, as explained in the previous summary of the fault sequence (p. 66). The field relations, as I see them, favor the view that fault D is older than the moderate caliche--hence, older than 10,000 years--but a younger age cannot be ruled out. Indeed, of all the former scarps created by faulting at site H-4, the latest movement on fault D is the only displacement for which signs of a steep scarp are still visible in the profile, although even this scarp is concealed along the present subdued scarp face by younger deposits--that is, the young colluvium. Preservation of the scarp, although faint, tends to favor the interpretation of comparatively recent movement on fault D. It is further possible that a small displacement could have occurred on fault D in the last 4,000 years, as is illustrated in the following remarks about the permissible freedom in interpreting the relations of the weak caliche soil to faulting.

The weak caliche soil is formed on colluvium near the present surface only downslope from fault D. This caliche is comparable to carbonate in the weathering profile found near Arco on alluvial fans younger than the Arco scarp. As discussed previously (p. 36), the weak caliche is thereby estimated to be less than 4,000 years old. Where the weak caliche ends upslope near fault D, a thin mantle of overlapping slope deposits pinches out by ascending a relatively steep contact approximately coincident with the fault. Notwithstanding inferences from landforms, which indicate that deposits of the last 4,000 years are not visibly involved in faulting, the terminus of the weak caliche could be a consequence of a few feet of offset on fault D, relatively down on the south, since the caliche formed. If so, this movement is no older than 4,000 years, according to the date estimated for the weak caliche. By this interpretation, the overlapping slope deposits pinch out against the low scarp that was then formed by this episode of faulting. On the other hand, despite these permissive and suggestive field relations, the geology agrees well enough with the interpretation that the weak caliche has not been involved with faulting.

Summary

Alluvial fans younger than half a million years old have been faulted along 9 miles at the foot of the Lemhi Range north of Howe, and probably also along another similar segment 4 miles long that continues north beyond a bedrock ridge. The faulting began more than 30,000 years ago and formed the step known as the Howe scarp. Faulting of fan gravel at site H-4 near the mouth of Black Canyon, 7 miles north of Howe, resulted in more than 50 feet of aggregate vertical offset, as measured by the scarp height. At this site, four or more episodes of movement on faults in a zone 80 feet wide caused 17 feet of measurable vertical offset before 30,000 years ago, as indicated by buried caliche soils and by the fault sequence deduced from the deposits and soils that were involved in the faulting. At least 10 feet of additional movement is demonstrable on one of these faults after 30,000 years ago, and equivocal relations between this fault and relic soil and younger colluvium allow the possibility that this offset occurred more recently than 10,000 years ago. Changes in scarp height between adjacent fans of differing age imply intermittent faulting along the Howe scarp, but such inferences from landforms do not indicate faulting of young fans of the last 4,000 years. Nonetheless, the terminus of an immature caliche soil near the pinchout of overlapping slope deposits at the present surface near the most recent fault at site H-4 permits the interpretation that its latest displacement is no older than 4,000 years.

Scarp at Mud Lake

General features and previous concepts

Mud Lake receives the discharge of Camas Creek, which heads 45 miles north in the Centennial Mountains at the Idaho-Montana boundary. The lake is accordingly surrounded by widespread lake and stream deposits that have been carried to the edge of the Snake River Plain in the geologic past. These more or less fine-grained deposits rest on basalt and are about 100 feet thick (Walker, 1964, pl. 2, section F-F'). Some of this detritus contains interbeds of local lava flows north of Mud Lake, and--as at other areas near the margin of the plain where streams debouch from the north--similar detrital deposits are interbedded in basalt at considerable depth; these sedimentary deposits pinch out southward toward the central axis of the plain (Walker, 1964, p. E14-E16, pl. 2). That is, buildup of basalt within the Snake River Plain has, for a long time, impeded the southward spread of sedimentary material. Because of the interplay of lava flows with lake and stream deposits, the topographic relief at the edge of the Snake River Plain, is quite subdued. Stearns (*in* Stearns and others, 1939, p. 37), for example, found deposits at an almost imperceptible divide immediately south of Circular Butte (S 1/2 T. 6 N., R. 32 E.) indicative of a former lake only 20 feet higher than Mud Lake, which nonetheless extended broadly over an area exceeding 140 square miles. This lake reached west into the area where Birch Creek and the Big Lost River end in playas.

Each additional increment of height expressed by detrital deposits above Mud Lake would imply progressively larger former lakes in this area, provided that the deposits actually accumulated in lakes, and provided further that their high position is not a consequence of tectonic uplift--by faulting, for example. It is the puzzling height of such fine-grained water-laid sedimentary deposits in a bluff (scarp) 95 feet above the north shore of Mud Lake at Clay Butte (fig. 15)

Figure 15.--NEAR HERE.

that has stimulated previous ideas that these deposits might have been recently elevated on a fault. Modern movement on the fault is supposedly implied by an earthquake felt by a nearby rancher in 1911 (Stearns and others, 1939, p. 43). The hypothesis of uplift along the scarp at Mud Lake is attractive because the opposite proposition that Clay Butte is preserved solely as an erosion remnant of lake deposits requires the former existence of an exceptionally large lake for which no other evidence has been found. A lake at the indicated height (on a landscape similar to the present) would have extended 30 miles southwest along the lowland of the Big Lost River into the central area of the NRTS, and the lake would have overflowed southeastward into the Snake River. Deposits that accumulated in such a lake, according to the proposition of erosion, would have been obliterated from a very wide area--hundreds of square miles--except for the solitary outcrop at Clay Butte. Perhaps because features of such a large ancestral lake are not evident, and because erosion on this scale seems improbable (especially if the low relief and the consequent impotence of streams is taken into account) published opinion on the origin of the scarp at Mud Lake favors its formation by faulting.

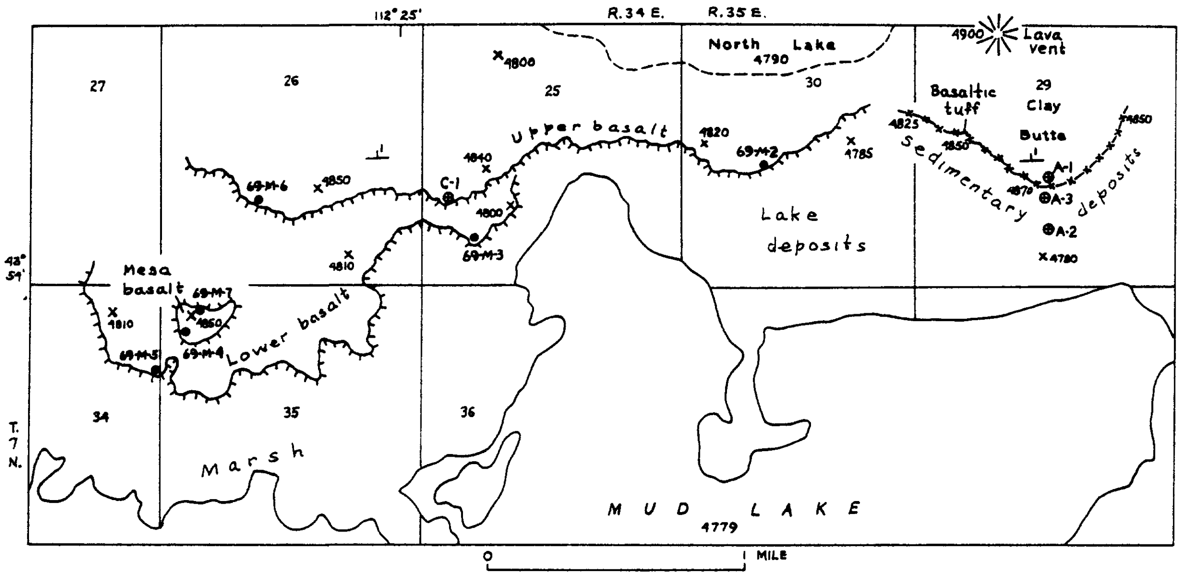

Figure 15.--Sketch map of area along the north shore of Mud Lake, showing geologic units, the position of surface samples (69-M-2 through -7), the sites of drill holes (A-1, -2, -3, and C-1), and other features discussed in the text.

The ideas about faulting at Mud Lake are derived mainly from the interpretation that the bluff north of Mud Lake is a fault scarp. In addition to the 95-foot bluff where Clay Butte faces Mud Lake, the scarp is also expressed by a rim of basalt 25-55 feet lower, which continues westward more than 3 miles from Clay Butte along a sinuous edge (see the unit identified as the upper basalt on fig. 15). Thus, the combined length of this scarp in sedimentary deposits and basalt is about 4 miles. Stearns (in Stearns and others, 1939, p. 43) attributed this scarp to a fault of the same length with a maximum uplift on the north of 50 feet. This inferred displacement presumably represents his estimate of the height of Clay Butte. He further suggested that this offset was only the last of other probable movements on the same fault, by which the basin around Mud Lake had been formed. Although Stearns did not give evidence for these conclusions, he apparently thought that a gentle northward slope of the basalt toward North Lake, namely the 1° dip of the upper basalt on figure 15, supported his concept of uplift at the scarp.

Bonilla and Chase (written commun., 1968) summarized the ideas of Stearns and observed that a distinctive layer of basaltic tuff (cinders) in the upper part of Clay Butte dips anomalously northward toward its probable source, a vent half a mile distant. This indicated to them the possibility that the faulting postulated by Stearns is younger than the volcanic activity.

Limits of fieldwork and principal results

Fieldwork for the present study was confined to the scarp along the north shore of Mud Lake because it was thought that the possible presence of a fault in this area could be tested by identifying the exposed geologic units in drill holes. Work in such a small area hardly could be expected to yield definitive answers on the origin of the scarp, and in fact the results obtained provide chiefly negative information: namely, that no geologic units are demonstrably displaced by faulting along the scarp. No information was obtained to account for the northward dip of the upper basalt along the west part of the scarp. If this basalt was not tilted by uplift, it must have had a source to the south that is now obscure. The drilling, however, produced some positive results, which suggest that the geologic history for this area is considerably more complicated than would be expected from available outcrops; the history apparently involves changes in local relief amounting to more than 100 feet that have probably been caused by the changing balance between erosion and the buildup of sediment and lava flows. It is likely that much of this sediment could have accumulated as alluvium, not as lakebeds, in the manner shown by stream deposition in the extraordinarily flat Riverine Plain of New South Wales, Australia (David, 1950, p. 93; Schumm, 1968); but this concept, which eliminates the need to assume widespread lakebeds, is a matter for future study. A proper understanding of the geology of the Mud Lake region, which would be tantamount to comprehending the origin of the scarp at Clay Butte, will require not only much additional drilling to define the subsurface stratigraphy but also wide-reaching geologic mapping, so as to unravel the complex interplay of lakes, streams, and lava flows, together with the effects of erosion by wind and water. Until such a study is completed, and the scarp along the north shore of Mud Lake is thereby satisfactorily explained, faulting in this ares, although not yet demonstrated, cannot be completely ignored. Thus, a comprehensive geologic investigation should be pursued if sensitive nuclear installations are planned for construction near Mud Lake.

Area of lava flows

An important part of the study of surface features along the scarp at Mud Lake was an examination of basaltic lava flows west of Clay Butte and the collection of samples from representative outcrops (fig. 15). Three lavas are present: a lower basalt that crops out as a virtually horizontal bench at an altitude between 4,800 and 4,810 feet; an isolated basaltic remnant informally designated as the mesa basalt, which rests at an altitude of 4,850 feet on poorly exposed sedimentary deposits above the lower basalt; and an upper basalt, also on sedimentary deposits, whose edge forms the scarp west of Clay Butte at altitudes between 4,820 and 4,850 feet. The upper basalt has a well-preserved initial surface, diversified by pressure ridges, which has apparently never been completely covered by sedimentary deposits--other than existing patches of eolian sand. The lower basalt is an easily recognized, slightly altered, subaerial lava with a diktytaxitic texture--a technical term signifying the presence of small, angular cavities between crystals of feldspar (samples 69-M-3 and 69-M-5). The mesa basalt is also diktytaxitic and is not greatly different in hand specimen from the lower basalt (samples 69-M-4 and 69-M-7). By comparison with other basalts in the Snake River Plain, I judge that the noticeable alteration of both the lower basalt and the mesa basalt indicates either burial for considerable time in an environment of percolating ground water or prolonged weathering at the surface. The upper basalt, however, is entirely fresh, except where its subaerial surface was oxidized at the time of eruption, and its texture is conspicuously fine grained and dense (samples 69-M-2 and 69-M-6). Petrographic details about these and other baaslts that were collected for this study are listed by G. H. Stone, The University of Oklahoma, in table 3, and discussed on page 108.

The description by Stearns about the position of the inferred fault in the basaltic area west of Clay Butte is ambiguous. He marked the fault on his geologic map (Stearns and others, 1939, pl. 3) as ending with a southwesterly curve at the SW. cor. sec. 25, a little more than 2 miles from Clay Butte. Thus, he drew the fault only as far as a place about midway along the margin of the basalt area. He described the fault, however, as trending west (the actual words are, "strikes east") a distance of 4 miles, whereby the sedimentary deposits of Clay Butte "give way to blue basalt that was uplifted at the same time." This language specifies the fault clearly enough as being placed along the length of the scarp formed by the edge of the fresh ("blue") upper basalt. Indeed, a route along this scarp is the only logical place where a fault could be inferred. I therefore understand from the remarks of Stearns that he identified the fault as represented by uplift of the upper basalt on the north from a position occupied by the lower basalt on the south, thus forming the scarp.

Hand specimens of the lower and upper basalts, however, as explained above, demonstrate that these basalts are different and that they cannot represent a single lava flow displaced by faulting. This conclusion in the field was supported several months later by the results of petrographic study (see p. 109). These basalts also differ markedly in topographic expression: surface relief on the exposed lower basalt has been obliterated, but the initial relief of pressure ridges on the upper basalt is largely intact. The only other test thus required to determine the presence or absence of a fault in the basalt area was the drilling of hole C-1 at the edge of the upper basalt to investigate whether other lava flows might have been involved in faulting or whether the lower basalt continues north beneath the upper basalt without offset. Basalt encountered at a depth of 52 feet in this drill hole--an altitude of 4,778 feet (p. 103)--petrographically resembles the lower basalt (sample 69-M-8, table 3). Because the altitude of the basalt concealed in drill hole C-1 is 20 feet lower than nearby outcrops of the lower basalt, if a fault is present, the indicated displacement is opposite from the sense of movement inferred by Stearns--namely, down on the north. Relief on a lava flow, however, commonly exceeds 20 feet, and I conclude that the results from drilling and petrographic study do not warrant the inference that any fault whatever exists along the scarp formed by the upper basalt.

Area of Clay Butte

Outcrop of basaltic tuff

The other fieldwork along the scarp north of Mud Lake consisted of a survey of the basaltic tuff in the upper part of Clay Butte, to determine its dip, and a search in the subsurface for this tuff and for other possibly identifiable beds, which might have been involved in faulting.

The tuff dips gently north, and its westernmost outcrop is approximately at grade with the surface of the upper basalt. It is nonetheless unlikely that the upper basalt and the tuff are related: the basalt is a subaerial lava flow, whereas the tuff is characterized by particles of glassy basalt marked with rinds of the yellowish-brown alteration product known as palagonite, whose presence implies deposition in water. Palagonite forms by the hydration of hot basaltic glass--a process that ordinarily happens when hot basalt enters a lake. This basaltic tuff, which crops out about 5 feet below the top of Clay Butte, at an altitude as high as 4,870 feet, thus provides either evidence of a former subaqueous environment at this altitude or evidence of uplift of water-laid deposits to this height. The exposed field relations are inadequate to decide between these alternatives. Either origin is possible. The northward dip of the basaltic tuff, for example, is not explicitly a consequence of uplift, as is suggested by the following argument. If the basaltic tuff formed by an eruption from the vent half a mile north of Clay Butte, as Bonilla and Chase supposed, or by eruption from any other nearby vent below the level of lake water, the tuff could have been dispersed widely on the lake floor of that time--even at altitudes considerably above its source. (A similar lacustrine basaltic tuff near Oreana, Idaho, in the western Snake River Plain, as shown on an unpublished geologic map by N. R. Anderson, University of Puget Sound, is traceable to altitudes several hundred feet above its subaqueous vent, although the enclosing lake deposits are undeformed.) In short, the north dip of the basaltic tuff does not necessarily indicate uplift. On the other hand, uplift cannot be ruled out by the field relations of the available outcrops. The possibility that the tuff might have been involved in faulting was accordingly explored by drilling.

Results of drilling

The search for identifiable beds in the subsurface was attempted by drilling to depths as great as 90 feet, mostly by taking drill cores, along a section that reaches from the top of Clay Butte to its base (fig. 16). (See also, the drilling records that begin on page 102.)

Figure 16.--NEAR HERE.

Surprisingly, basalt was encountered in hole A-1 at a depth 61 feet below the top of Clay Butte, although no basalt crops out around the immediate periphery. This basalt was again located in hole A-3, midway on the slope, where it was cored continuously to its base, through a thickness of 22 feet. Samples 69-M-9 and 69-M-10 from the massive lower part of this basalt were thereby obtained. The petrography of these samples resembles that of the lower basalt west of Clay Butte (p. 109). Moreover, the altitude of the surface of this basalt in Clay Butte is between 4,805 and 4,814 feet, which is comparable to the altitude of the lower basalt. Also, like the lower basalt, the basalt in Clay Butte appears to lie more or less horizontal. I conclude that the concealed basalt in the subsurface of Clay Butte is indeed the lower basalt that crops out in the area to the west. The lack of noticeable offset in altitude between the lower basalt in Clay Butte and its outcrop 2 miles west does not favor the concept of faulting along the scarp north of Mud Lake. Indeed, the similarity in altitude for the basalt at these places suggests that no fault exists. This inference is compatible with the results of drilling at the base of Clay Butte.

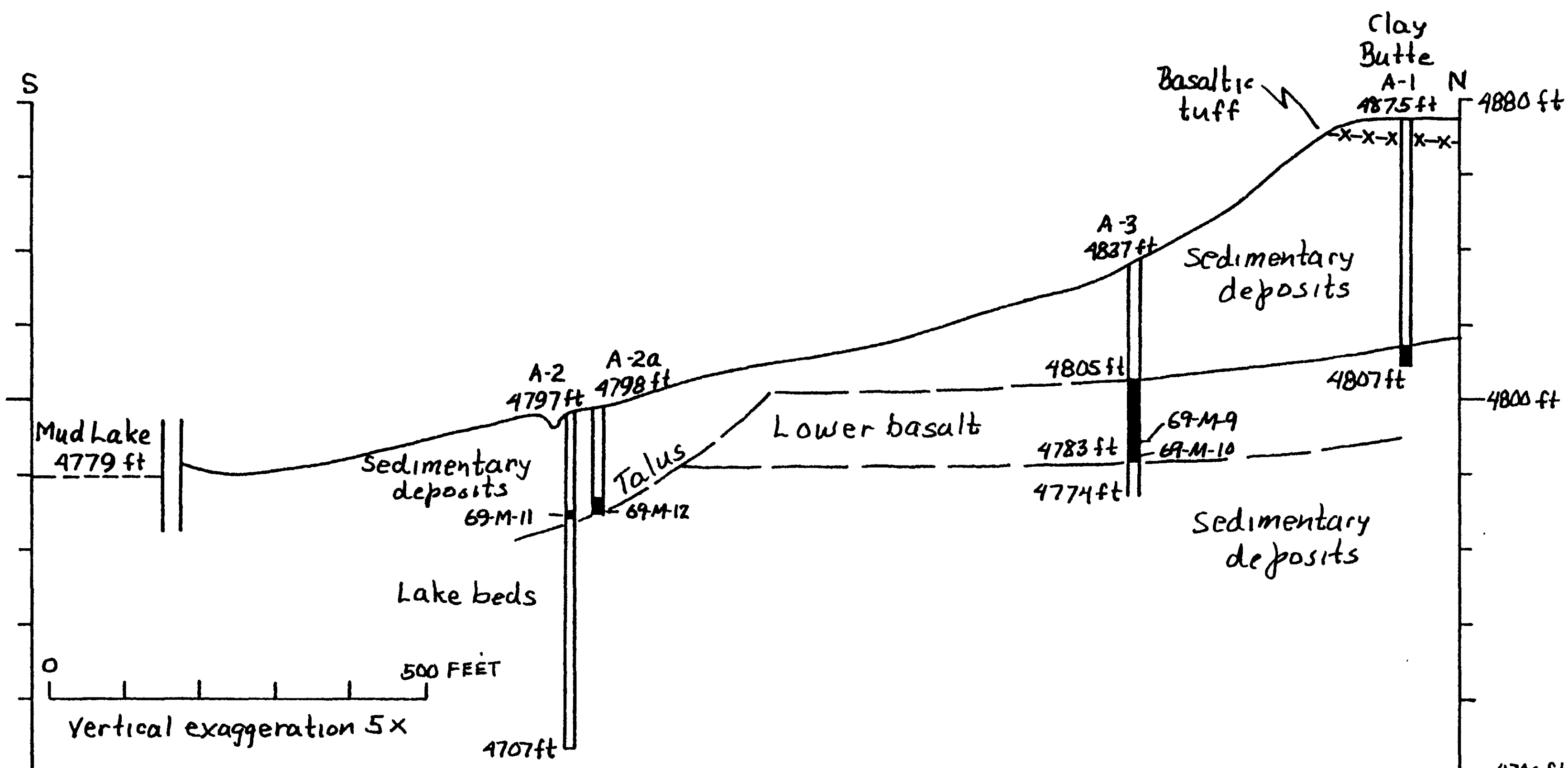

Figure 16.--Section through drill holes between Clay Butte and Mud Lake, showing principal stratigraphic units and position of samples.

Drilling at the base of Clay Butte was done at two sites, 25 feet apart. The deeper hole, A-2, after passing through a block of basalt between 27.5 and 29.0 feet below the surface (see below), entered thin-bedded clay and silt indicative of lakebeds at a depth of 45 feet, and these beds persisted to the bottom of the hole, at an altitude of 4,707 feet. If the concealed basalt in Clay Butte has been uplifted by faulting from a position below Mud Lake, regardless of the correctness of its correlation with the outcropping lower basalt, the indicated displacement is accordingly more than 100 feet. That is, the evidence determined by drilling fails to confirm the 50 feet of offset at Clay Butte inferred by Stearns. An offset exceeding 100 feet, however, is geologically unreasonable. The supposed fault trace along the scarp north of Mud Lake is only 4 miles long--even shorter if the results from drill hole C-1 are taken into account--and fault movement of 100 feet in so short a distance is highly unlikely; historic high-angle faults elsewhere in North America are ordinarily at least a mile long for every foot of offset (M. G. Bonilla, oral commun., 1969). It is also geologically unreasonable, assuming that the basalt in Clay Butte is correctly identified as the lower basalt, that this basalt could lie at a depth below an altitude of 4,707 feet in hole A-2 and nonetheless crop out as a level bench 2 miles west at an altitude of 4,800 feet. The basaltic tuff in the upper part of Clay Butte also was not identified in hole A-2.

In summary, the drilling fails to demonstrate displacement by faulting along the scarp formed by Clay Butte. The only alternate interpretation of the drilling data is that hole A-2 may have accidently passed through an inclined fault plane, thereby missing the lower basalt. Although a coincidence of this kind is extremely unlikely, further drilling should be done at the base of Clay Butte in the event that nuclear installations are to be located nearby.

Former changes in topography

The materials penetrated by drilling at Clay Butte, although not giving support to the concept of faulting, provide several hints about unexpectedly complex topographic changes between accumulating deposits and features of erosion. These changes in height of the local terrain suggest that scarps formed in the past, perhaps solely by erosion, in ways that resemble the present scarp north of Mud Lake. If so, the abrupt relief in this area that stimulated ideas about faulting has been misinterpreted. My understanding of the former changes in topography, although necessarily based only on scant data, derives from the outcrop of the palagonitized basaltic tuff, from the presence of the concealed lower basalt, and from the discovery of loose blocks of basalt that have been buried at the base of Clay Butte.

The block of basalt found at a depth of 27.5 feet in hole A-2 was cored through. This basalt core (sample 69-M-11) shows none of the distinctive attributes by which either the top or the bottom of a lava flow is recognized, and indeed the core is dense and massive throughout. It was concluded in the field that this basalt is a separate piece, probably a talus block, but more or less certainly a marker of former erosion at its place of rest. Curiously, the petrography of sample 69-M-11 does not correspond at all closely with that of any other lava flow collected thus far in the Mud Lake area. Several explanations for the source of this loose block of basalt come to mind, none of which can be tested from evidence now available. I therefore leave the matter of the source of this block to another time, but I accept the block as evidence of former erosion.

Because of the curious basalt block found in hole A-2, hole A-2a was drilled nearby, with the result that a somewhat larger block was encountered at a depth of 25.0-29.5 feet. This block, although containing a vesicular zone from 26.5 to 27.5 feet, also lacks the features of either the top or the bottom of a lava flow, and it is also evidently a loose piece. Sample 69-M-12 from a core through this block raises none of the difficulty of identification presented by the other block; it resembles the concealed lower basalt sampled in drill hole A-3 (p. 109). It appears, therefore, that subaerial debris (talus) from the lower basalt lies on eroded lake deposits below the present base of Clay Butte at an altitude of 4,768 feet, which is more than 10 feet below the present level of Mud Lake.

A possible sequence of topographic change at Clay Butte, as expressed by these loose blocks, and by outcrops and other features located by drilling, is as follows. Lake and stream deposits accumulated to an altitude of about 4,785 feet, after which the lower basalt erupted on a subaerial landscape as a lava flow 20-25 feet thick. Subsequent erosion progressed as low as an altitude of 4,768 feet, as marked by talus blocks below the edge of the basalt. This erosion may have occurred after additional sedimentary material that contains the layer of basaltic tuff had been laid down on the lower basalt. If so, the erosion scarp would have been accordingly more than 100 feet high. On the other hand, the basaltic tuff may date from a buildup of sediment after the talus formed, and the erosion scarp may have been no more than 35 feet high. In this event, the depth of sedimentary deposits that covered the talus blocks exceeded 100 feet.

Sequences that are even more complicated and that involve the mesa basalt, the upper basalt, and possibly subaerial sediment, can also be inferred. The most significant aspect of these sequences for the present discussion of the scarp at Clay Butte is that past differences in topography amount to more than 100 feet, as shown by changes between erosion and the buildup of sediment and lava flows. Whatever was the exact order of these events, the present bluff at Clay Butte is understandable as a modern erosion scarp comparable to those indicated in the past.

Drilling records

Drilling for this study at Mud Lake was done under the supervision of Eugene Shuter, U.S. Geological Survey, from May 7-16, 1969. Hole C-1 was cored throughout. The upper parts of holes A-1, A-2, and A-2a were drilled with a hollow-stem auger, taking drive-core samples at frequent intervals. The lower parts of these holes and all of hole A-3 were made with a core drill. The drilling logs are given below. (For locations of drill holes, see fig. 15.)

Log of drill hole C-1 in SW 1/4 sec. 25, T. 7 N., R. 34 E.,

near Mud Lake, Idaho

[Altitude 4,830 ft]

	Depth (ft)
Topsoil	1.0
Basalt, broken	2.5
Basalt, hard and dense	8.0
Basalt, broken and vesicular	9.5
Sand and silt, pale-brown	12.0
Clay, silty, pale-gray	15.0
Silt, sandy (no core recovered)	32.0
Sand, very fine, silty, soft and loose; water at 48 ft (no core recovered)	52.5
Basalt, broken	54.0
Basalt, vesicular and hard	56.2
Basalt, hard; sample 69-M-8 taken at 60 ft	60.3

Log of drill hole A-1 in S 1/2 sec. 29, T. 7 N., R. 35 E., on Clay Butte, near Mud Lake, Idaho

[Altitude 4,875 ft]

	Depth (ft)
Sand, medium, gray-brown	5.0
Sand, fine, brown[1]	8.0
Sand, fine, silty, pale-brown	10.0
Silt, fine, sandy, firm, pale-brown	15.0
Sand and clay, slightly plastic, dark-brown	20.0
Clay, brown; some fine sand	30.0
Blocky clay, gray-brown; limonite stringers	31.5
Clay, gray-brown	40.0
Silt, brown	50.5
Sand, brown, fine to medium	61.0
Basalt	68.0

[1] Basaltic tuff in this interval mixed in cuttings.

Log of drill hole A-2 in S 1/2 sec. 29, T. 7 N., R. 35 E., at base of Clay Butte, near Mud Lake, Idaho

[Altitude 4,797 ft]

	Depth (ft)
Silt, light gray-brown	5.0
Silt, sandy, gray-brown	10.0
Sand, fine, silty, brown; limonite stringers	11.5
Sand, medium, silty, brown	21.5
Silt, sandy, brown	27.5
Basalt; sample 69-M-11 taken at 28.5 ft	29.0
Sand, fine to coarse; black, brown, and gray	45.0
Clay and sand	48.0
Clay	55.0
Silt, sand, and clay	65.0
Sand, sandy clay, silt, and clay; thin bedded	90.0

Log of drill hole A-2a in S 1/2 sec. 29, T. 7 N., R. 35 E.,

at base of Clay Butte, near Mud Lake, Idaho

[Altitude 4,798 ft]

	Depth (ft)
Silt and sand, brown--	25.0
Basalt; dense, vesicular from 26.5 to 27.5 ft; sample 69-M-12 taken at 29 ft----------------------------------	29.5
Sand, fine to coarse--	30.0

Log of drill hole A-3 in S 1/2 sec. 29, T. 7 N., R. 35 E., on slope of Clay Butte, near Mud Lake, Idaho

[Altitude 4,837 ft]

	Depth (ft)
Silt, blocky, brown	10
Clay, silty, brown	24
Clay	27
Sand	29
Clay; stringers of sand	32
Basalt; sample 69-M-9 taken at 50.5 ft; sample 69-M-10 taken at 53 ft	54
Silt, sand, and clay; hard	63

Petrography of basalt samples

Samples of basalt collected for this study near Mud Lake, from outcrops and drill holes, were sent for petrographic examination to G. T. Stone, The University of Oklahoma, while he was pursuing other studies of basalts from the Snake River Plain at the University of Cambridge, England. His descriptions from microscopic study of thin sections that were cut from these samples are summarized in table 3. Only the properties that are thought to be useful for showing similarities and contrasts are listed. For example, aspects of the groundmass plagioclase and the opaque minerals, which exhibit little distinctive change, are omitted. Readers who are interested in the technical terms employed by Stone will find exacting definitions and informative discussions of their significance in standard textbooks (for example, Williams and others, 1954), and this terminology accordingly needs no further explanation here. For other readers who have only a passing interest in such technical matters, it is perhaps enough to read from the table that the various samples are described in similar and dissimilar terms, depending on their correlation--or lack of it.

Table 3.--*Petrographic properties of basalt samples from Mud Lake area*

[Determined by G. T. Stone]

Rock unit	Sample No.	Texture	Microphenocrysts	Groundmass minerals		Residuum		Significant secondary substances	Remarks
				Olivine	Augite	Approx. quantity (in percent)	Description		
Upper basalt----	69-M-2	Hyalopilitic; a few small vesicles.	A few small crystals of olivine ($\leq$ 0.5 mm) and plagioclase ($\leq$ 1.0 mm).	Common--	Trace incipient needles.	50	Opaque glass--------	Trace amygdalar calcite--	
	6	Hyalopilitic to hyalo-ophitic; small vesicles common.	Olivine ($\leq$ 0.8 mm) and plagioclase, some in clusters; trace picotite in olivine.	--do----	Almost none----	55	---do---------------	---do--------------------	
Mesa basalt-----	4	Subophitic to ophitic; diktytaxitic.	A few olivine crystals ($\leq$ 1.0 mm), picotite inclusions.	Abundant	Grayish to pinkish tan.	15-20	Crystallitic, some brown glass.	Incipient iddingsite after olivine.	Fragment of a partly absorbed olivine crystal.
	7	Intersertal to intergranular; diktytaxitic.	Olivine crystals ($\leq$ 1.0 mm) in clusters, trace picotite.	--do----	Pink to orange-brown sheaves.	30	Dark, crystallitic--	Incipient iddingsite after olivine; trace amygdalar calcite.	
Lower basalt----	3	Intergranular to subophitic; numerous small vesicles.	A few olivine crystals ($\leq$ 1.0 mm).	--do----	Grayish, pinkish, and orangish tan.	20	Crystallitic, trace glass.	Trace intersertal calcite; iron oxide patches in residuum.	
	5	Subophitic to ophitic; diktytaxitic.	A few small olivine crystals ($\leq$ 0.8 mm).	--do----	Pinkish to orangish tan.	20	---do---------------	None--------------------	
Lower basalt (?) (Drill hole C-1).	8	Intersertal to intergranular; numerous small vesicles.	Scarce------------------	--do----	Pinkish tan------	30	---do---------------	---do--------------------	Large patch of partly crystallized residuum.
Lower basalt (?) (Drill hole A-3).	9	Subophitic; diktytaxitic; numerous small vesicles.	Scarce very small olivine crystals ($\leq$ 0.5 mm), some clusters, trace picotite.	--do----	---do------------	15	Crystallitic; some brown glass.	---do--------------------	
	10	Intergranular to subophitic; diktytaxitic.	Small olivine crystals ($\leq$ 0.6 mm) in clusters; scarce plagioclase	--do----	---do------------	12	Some brown glass----	---do--------------------	Some long vesicles ($\leq$ 5 mm) with borders of residuum.
Buried talus (Drill hole A-2a).	12	Intersertal to intergranular; diktytaxitic.	A few conspicuous olivine crystals ($\leq$ 2.0 mm) in clusters; scarce plagioclase.	--do----	Pinkish-tan sheaves.	20-25	Crystallitic; trace glass.	Trace intersertal calcite; discontinuous streaks of iron oxide in residuum.	
Buried talus (Drill hole A-2).	11	Hyaloophitic; slightly vesicular.	Scarce small olivine crystals.	Common--	Incipient crystals	50	Largely opaque; crystallitic; much skeletal plagioclase.	None--------------------	Probably different from other samples.

Correlation by petrography alone is difficult, even after fairly careful examination, especially among rocks as similar as the basalts of the Snake River Plain. Stone nonetheless acknowledges that the characteristics seen with a microscope are consistent with the correlations suggested by the field relations (written commun., Sept. 16, 1969), and he comments further that samples 69-M-3, -5, -8, -9, -10, and -12 (all lower basalt and its correlatives) are "very similar" (written commun., Oct. 16, 1969). Stone finds picotite in olivine only in samples 69-M-4, -6, and -7, and this circumstance suggests that the mesa basalt might be an outlier of the upper basalt; but other aspects of the petrography (the texture, the groundmass augite, the character of the residuum, and the presence of iddingsite after olivine in the mesa basalt) indicate that these basalts are different. This conclusion from petrography is supported by the field relations. Sample 69-M-11 from a buried talus block "seems distinctly different," and indeed this sample differs also from the composition of virtually all other basalts in the Snake River Plain. Thus, sample 69-M-11 is both a petrographic and a geological enigma (p. 100).

Age of scarp

The time of formation of the scarp north of Mud Lake is, of course, limited by the ages of the sedimentary deposits and lava flows in which the scarp is defined. Unfortunately, the ages of these geologic units can be only vaguely estimated. Even so, from the evidence discussed below, it is likely that the scarp is about 15,000 years old, or older.

From sedimentary deposits of the Mud Lake basin, Stearns (in Stearns and others, 1939, p. 37-38) mentioned a toe bone of an extinct camel 45 feet below the surface in sec. 15, T. 7 N., R. 33 E., from which he inferred that "the lake was probably formed in early Quaternary (Pleistocene) time and has continued into Recent time, being now represented by the much smaller Mud Lake." By this scanty evidence, the scarp is no older than Pleistocene.

Features of the upper basalt permit a somewhat closer estimate of age for the scarp. Where this basalt slopes gently downward to the ephemeral water of North Lake, blocks of vesicular lava at the basalt surface have been heaved and broken by the process of freeze and thaw, thus producing some of the features of patterned ground that have been noted elsewhere in the Snake River Plain (Malde, 1964). I have interpreted patterned ground of this kind as having been produced by the cold climate of the Pleistocene--hence, more than 10,000 years old. This inference is supported by the presence of exfoliating weathering rinds about half an inch thick on pieces of the upper basalt, as well as by the destruction of original glassy skins on the surfaces of ropy lava. Weathering rinds as thick as half an inch are common on exposed basalt boulders that were carried along the Snake River about 30,000 years ago by the Bonneville Flood (Malde, 1968, p. 10, fig. 18). Despite these effects of weathering, however, the myriad irregularities at the surface of the upper basalt that formed during its eruption, mainly pressure ridges, are largely intact. Weathering of the upper basalt has therefore lasted about 30,000 years, or longer, but not long enough to modify its initial relief.

Talus blocks derived from the upper basalt along the scarp north of Mud Lake lack exfoliating weathering rinds, although these blocks are mainly coated with caliche crusts indicative of a caliche soil. The talus thus began to form more than 10,000 years ago, perhaps more than 30,000 years ago (see the discussion on caliche soils at the Arco scarp, p. 36-42, and at the Howe scarp, p. 74-80).

Near the base of the scarp north of Mud Lake, below the edge of the upper basalt at an altitude of 4,790 feet near the center of sec. 30, T. 7 N., R. 35 E., are many rounded basalt boulders, all of which were derived by erosion of the upper basalt. Some of these boulders are as large as 2 feet in diameter. They evidently represent rolled pieces of former talus that was washed by wave action when Mud Lake was about 10 feet above its present level. These boulders have exfoliating weathering rinds about a quarter of an inch thick. Although these rinds suggest weathering less prolonged than that demonstrated by the thicker rinds on boulders carried by the Bonneville Flood, they nonetheless indicate that the boulders have been exposed for a considerable time, probably at least 15,000 years.

In summary, weathering of the upper basalt and its erosion products suggests that the scarp north of Mud Lake is partly defined by a basalt at least 30,000 years old, and that the scarp has existed during the last 10,000-15,000 years, perhaps much longer.

Summary

A scarp north of Mud Lake that is defined by a bluff 95 feet high in sedimentary deposits at the east end (Clay Butte), and by a rim of fresh basalt 25-55 feet lower on the west, has been previously interpreted to be an effect of uplift by recent faulting. Drilling along the scarp, however, has failed to identify any geologic unit involved in faulting. Rather, a concealed basalt found by drilling, which is apparently equal to an exposed bench of lower basalt below the rim on the west, suggests that no fault is present. Correlation of the lower basalt is supported by petrographic comparisons. Thus, the exposed lower basalt at the west part of the scarp extends north beneath the scarp as a concealed layer. If the lower basalt is offset, the displacement was a few feet relatively down on the north--not an uplift coincident with the scarp. The lower basalt is also concealed in Clay Butte at the same altitude as its outcrop on the west, and this circumstance further suggests a lack of offset. Drilling at the base of Clay Butte, at the toe of the scarp, reached a depth 100 feet below the lower basalt but penetrated only lake beds in the lower part of the hole. If a fault is present at this part of the scarp, either the displacement exceeded 100 feet, which is geologically unreasonable, or the drill hole accidently passed through the fault plane, which is highly unlikely.

The drilling, on the other hand, revealed features that imply former changes in local relief amounting to more than 100 feet, which were probably caused by a changing balance between erosion and the buildup of sediment and lava flows. The present scarp is therefore understandable as a modern erosion feature comparable to erosion scarps that existed in the past. Only a small part of the region, however, was examined during this study, and the origin of the scarp along the north shore of Mud Lake is still inadequately explained. Faulting in this area, therefore, although not yet demonstrated, cannot be completely ignored. A comprehensive geologic study should thus be made if nuclear reactors are planned for installation near Mud Lake.

Principal lineament

General features

On the lava plain in the east part of the NRTS, Bonilla and Chase (written commun., 1968) recognized a virtually continuous linear feature marked by differences in vegetation, but perhaps related to emplacement of the basalt, extending some 17 miles about N. 10°E. from East Butte (fig. 1). They referred to this feature as the principal lineament and recommended additional geologic work on its origin and age so that its future behavior might be predicted.

The principal lineament is indeed conspicuous from the air, appearing on aerial photographs taken in October 1949 for the Idaho Operations Office as an abrupt and regular boundary between light-toned terrain on the west and dark-toned terrain on the east. The boundary further coincides in most places with a broken white streak. As thus defined, the lineament follows a curved path from the center of sec. 11, T. 2 N., R. 32 E., to the center of sec. 36, T. 3 N., R. 32 E., and thence takes a route of surprising straightness to the west boundary of sec. 21, T. 5 N., R. 33 E. The principal lineament is equally distinct on aerial photographs taken in July 1954 for the Army Map Service, but the white streak appears dark.

As seen from the air, the principal lineament is superimposed on a bewildering variety of surface features of the lava plain that formed during lava eruptions, including lava lobes, pressure ridges, the flanks of scattered vents, and various kinds of depressions caused by collapse of solidified lava crusts in areas undermined by fluid outflow (fig. 17).

Figure 17.--NEAR HERE.

The mingling of such volcanic features produces a chaotic array, hard to describe adequately in words, but forming the familiar landscape of a lava terrain, as is exemplified at Craters of the Moon National Monument west of the NRTS. The interplay of lava movement represented by these features resulted in a topographic relief of about 25 feet, locally as much as 100 feet, on the lava plain. Some of the local relief along the principal lineament, however, formed after the lava cooled, by rather ineffectual erosion along drainage routes that persist only short distances in troughs of initial irregularities. Despite the extraordinary abruptness of the principal lineament, all the various eruptive features and drainage routes cross the lineament without interruption. Moreover, the volcanic aspects of the lava plain as seen from the air, to the west and east of the lineament, notwithstanding the obvious tonal contrast, are virtually equally clear. That is, the character of the volcanic terrain does not change at the lineament. According to this observation, whatever is the explanation for the lineament, it formed by surficial processes after the lava solidified. In short, the principal lineament apparently is not at all a feature that formed during emplacement of the basalt. This matter is further discussed below (p. 131).

Figure 17.--Vertical aerial photograph of about 9 miles of the principal lineament marked by an abrupt change from lighter to darker tone along a north-south line to the right of center. This stretch of the lineament extends from the NE. cor. sec. 32, T. 5 N., R. 33 E., at the north, to the center sec. 7, T. 3 N., R. 33 E., at the south. A trench excavated in sec. 7 is near the south edge of this photograph. The area covered by this photograph is outlined on figure 1. (From Army Map Service aerial photograph 121-AL-5192 taken July 22, 1954.) North is at top of photograph.

At ground level, the vegetational differences that distinguish the principal lineament are fairly subtle for the inexperienced eye, although a botanist would undoubtedly comprehend the contrast immediately.

The position of the lineament itself is generally clear enough, being commonly marked by a rather dense stand of ryegrass and by scattered tall sagebrush, which define a narrow band about 200 feet wide. During spring and early summer, the ryegrass is green and gives these segments of the lineament a dark tone, as in the Army Map Service aerial photographs. At other times, the dry and yellow ryegrass gives the lineament a light tone and accounts for the broken white streak seen from the air. During autumn, sagebrush scattered among the ryegrass blooms luxuriantly, in contrast with meager blooms on nearby sagebrush. Altogether, vegetation along the lineament at such places reflects conditions of relatively favorable soil moisture. As explained below, this moisture is apparently held by a thin layer of sand that coincides with the lineament.

The contrast between neighboring areas to the west and east of the principal lineament is compounded from several rather small differences in vegetation. The plants of both areas are substantially the same, but their abundances are different. So are the soils in which these plants grow. The area to the east is simple to describe in general terms: a more or less monotonous and dense cover of sagebrush, which is typical of most parts of the lava plain, gives the landscape a drab tone. Cushion plants among the sagebrush hinder erosion of the silty soil. West from the lineament the vegetation is diverse and includes many plants not abundant in other areas: among them, rabbit brush, Russian thistle, prickly pear cactus, and clumps of ryegrass. Scattered sagebrush blooms feebly in autumn. This assemblage is recognizable along a zone as much as 2 miles wide. Much of the ground is barren, and the remainder is conspicuously sandy. Rabbit droppings are everywhere. The sand and ryegrass indicate an affinity with characteristics of the broken band of ryegrass along the principal lineament. Such tracts of mixed vegetation remind me of places elsewhere on the Snake River Plain recently uncovered by deflation of drifting sand and not yet stabilized by the dominant sagebrush of the vegetational climax.

A common attribute of the principal lineament in those segments marked by bands of ryegrass is a scalloped eastern edge, which is formed by repeated lobes that extend irregularly several tens of feet from the lineament, roughly elongated toward the northeast. Like the main part of the lineament, the lobes are thin sheets of sand loosely anchored by ryegrass. The lobes appear to be a secondary aspect of the lineament that has formed recently (or currently) by the force of prevailing winds, which sweep diagonally northeastward and cause sand along the lineament to migrate. Indeed, in secs. 25 and 36, T. 3 N., R. 32 E., a thin and discontinuous sheet of sand that originates at the principal lineament is more or less actively drifting about N. 40°E. along a broad belt that turns gradually northward at increasing distance until, some 10 miles from its apparent source at the lineament, the trend of the sand belt is virtually the same as the trend of the principal lineament. From that place, the belt of drifting sand continues parallel to the lineament at a distance of about 3 miles an additional 8 miles north (fig. 1). The light-toned streaks in the southeast corner of figure 17, sparsely held by vegetation, if at all, are part of this belt of sand. The possible significance of this belt for understanding the lineament is discussed on page 135. A short distance south, in sec. 1, T. 2 N., R. 32 E., discontinuous streaks of drifting sand trend from the lineament in a direction N. 70°E. Curiously, none of these bodies of sand have a recognizable tie with areas west of the lineament, although other discrete sheets of drifting sand in those areas are found several miles distant. Such relations indicate that the principal lineament is a comparatively unstable surficial feature vulnerable to the power of recently active (or present) winds.

Relation to lava outcrops

Traced along its length, the principal lineament (meaning either the prevalent broken narrow band of dense ryegrass or the coinciding vegetational boundary) climbs and descends many irregularities in its path, as previously noted from the air, and persists with astonishing linearity across broad featureless tracts of smooth terrain. The places with surface irregularities on the lava plain provide most of the opportunities to search for a possible association of the lineament with faults. My search for faults, however, throughout the length of the lineament, was fruitless. Indeed, several outcrops were located that are demonstrably unbroken at the lineament. A few examples will suffice.

In the center of the west half of sec. 19, T. 3 N., R. 33 E., a stream bed intersects the principal lineament perpendicularly and exposes lava unbroken by faulting. Pressure ridges nearby along the lineament are also unfaulted. Farther north in the SE 1/4 sec. 6, T. 3 N., R. 33 E., the lineament climbs a lava ridge 25 feet high where the surface of the basalt is completely exposed--and unbroken. A vertical displacement of as little as a foot would be easily seen. Again, in the NW 1/4 sec. 20, T. 4 N., R. 33 E., the steep side of a pressure ridge is fully exposed a distance of 200 feet across the lineament and shows neither vertical nor lateral displacement by faulting. Finally, near the NW corner sec. 17, T. 4 N., R. 33 E., the lineament ascends to an unbroken flat lava upland where a vertical offset, if present, would be conspicuous.

Bonilla and Chase (written commun., 1968) indicated that a rounded, west-facing scarp about 15 feet high that formed during eruption of basalt in sec. 16, T. 5 N., R. 33 E. was along the lineament. This slope is part of the east rim of a collapse area shaped like a violin, still undrained by surface streams, and floored with playa deposits at the north end. The south rim that crosses the projected trend of the lineament, at the tailpiece of the violin, is a similar steep slope in basalt, but is unbroken. Columnar joints perpendicular to the basalt surface along the trend of the lineament indicate a jointed crust that rotated when subsurface liquid immediately west drained away. A phenomenon of this kind is characteristic of most lava terrains on the Snake River Plain and, indeed, can be seen at many other places nearby. Because the northward reach of vegetation differences used to distinguish the principal lineament is last recognizable 1 mile south, although very faintly, I exclude the extension of the lineament to this collapse area. On the other hand, I concur with the interpretation of Bonilla and Chase that a channel-like feature, which evidently formed during emplacement of the basalt, crosses the lineament with no apparent vertical or horizontal displacement in the southwest corner of sec. 20, T. 4 N., R. 33 E. This channel is almost surely a collapsed lava tube older than the lineament.

Features exposed by excavation

A conspicuous band of ryegrass about midway along the principal lineament in the north part of sec. 7, T. 3 N., R. 33 E., was selected for excavation to study its internal features (fig. 18). This site is

Figure 18.--NEAR HERE.

within a broad area of low relief, but basalt fragments that litter the surface to the west and east indicate that lava is present at shallow depth. The band of ryegrass along this part of the lineament stretches nearly half a mile and is about 200 feet across. Sandy soil is conspicuous, and it forms a scalloped eastern edge for the lineament, as explained in the remarks above.

The shallow surficial deposits across this band of ryegrass were first explored by making a series of augur holes by hand from west to east. These holes showed that the ryegrass is rooted in a surface layer of loose sand as much as 2 feet thick, which overlies compact calcareous soil (hardpan). The augur holes also showed that topographic relief along the buried surface of the basalt is gradual.

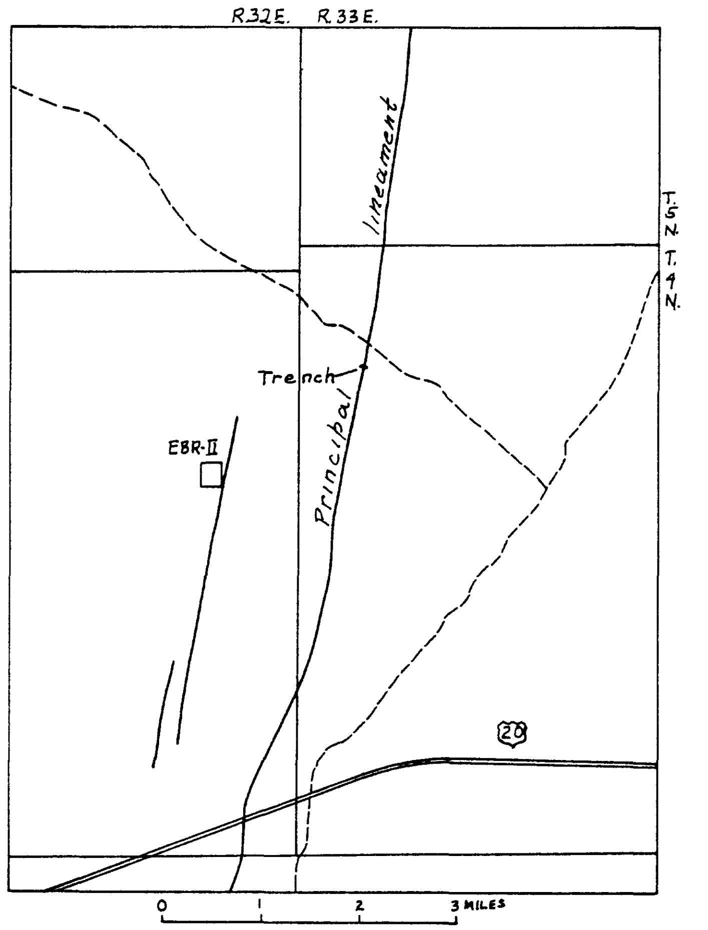

Figure 18.--Sketch map showing site of trench excavated across the principal lineament.

A trench 300 feet long, reaching to the west and east beyond the ryegrass, was then excavated to the basalt. The basalt surface was thereby completely exposed, and changes along the profile of the surficial deposits could be studied (fig. 19). The original vesicular

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Figure 19 .--NEAR HERE.

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surface of the basalt is intact along this trench and rises gradually from a depth of 5 feet in the west part to a position near the surface in the east part. The change in altitude of the basalt surface evidently expresses a gradual initial relief, which formed by gentle deformation of the lava crust by flowage while the lava cooled. At no place along the trench can evidence be found of faulting.

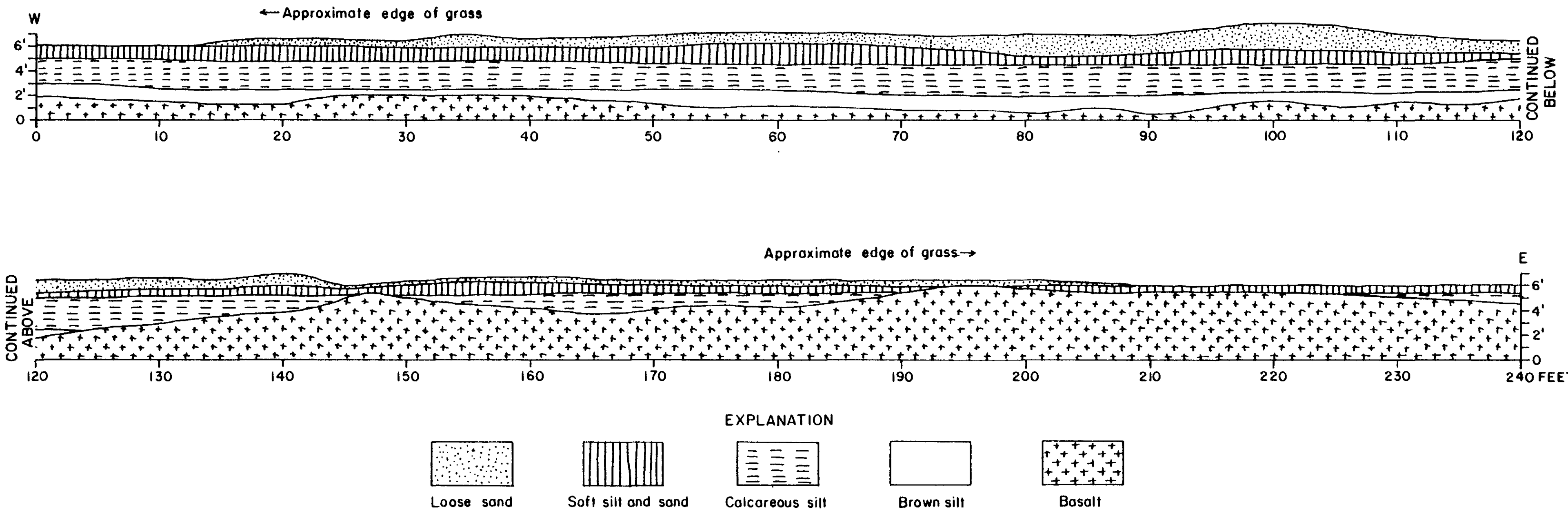

Figure 19.--Profile sketch of surficial deposits exposed in a trench excavated to basalt across a band of ryegrass that marks the principal lineament in sec. 7, T. 3 N., R. 33 E.

A representative section of the surficial deposits on the basalt in the western part of the trench is given in the description that follows:

<u>Typical profile in deposits on basalt at trench across principal lineament</u>—/

	Thickness (feet)
Ryegrass and scattered sagebrush at top.	
1. Sand, brown (10<u>YR</u>5/3, dry), loose, structureless; held in place by roots of ryegrass; distribution coincides with lineament------------------------------	1
2. Silt, sandy in upper part, pale-brown (10<u>YR</u>6/3,dry), soft and very friable, faint very thin platy structure in upper part, non-plastic but very slightly sticky when wet, effervesces with acid-----------------------	1 1/2
3. Silt, very pale brown (10<u>YR</u>7/3), strongly calcareous, dries with coarse mottles of white carbonate, hard when dry (difficult to augur by hand), plastic and sticky when wet; lower boundary gradual----------------	2 1/2
4. Silt, pale-brown (10<u>YR</u>6/3), soft and friable, massive, non-plastic but very slightly sticky when wet, effervesces with acid----------------------------------	1/2
Basalt at base.	

—/Terminology adapted from Soil Survey Manual, U.S. Dept. of Agriculture Handbook No. 18, 1951. Color designations are Munsell symbols.

Only the upper units in this profile are continuous across the lineament. The calcareous hardpan (unit 3) pinches out on the subdued pressure ridges of basalt at the east, and the brown silt below occurs only where the depth to basalt is at least 4 feet.

Origin

Although the superficial character of the principal lineament on the lava plain is clear enough, being a contrast in vegetation related to abrupt differences in soils, an explanation for these differences is still elusive. The present knowledge of the field relations, partly described above and further interpreted below, favors an origin by wind, but the implied direction of drift (N. 10°E.) differs from the present trend of prevailing winds in this region (about N. 50°E.). Whatever the uncertainty, however, an origin either during emplacement of lava or by faulting can be rejected.

The intricate variety of initial volcanic features that pass beneath the lineament without change, as emphasized in the preceeding remarks, rules out any chance that the lineament formed during lava eruptions. Moreover, the lavas themselves also cross the lineament without lithologic change, as determined by close comparison of hand specimens at several sites, although the various lavas along the lineament differ from place to place. Thus, a relation between the lineament and emplacement of lava would require a congruence of lava features that formed by several eruptions, and such a coincidence would be virtually impossible. Even a linear boundary for a single lava flow is unlikely, because other lava flows of the Snake River Plain have boundaries that are intricately lobate (see, for example, the map by Malde and others, 1963). Considering further that other analogous lineaments nearby trend parallel with the principal lineament (p. 140), a common origin for all by lava emplacement would far surpass scientific credibility.

I reject an origin for the principal lineament by faulting because of my failure to find (or recognize) the required faults. The direction of the lineament also differs markedly from the trend of other features of the region indicative of crustal fractures: the northwesterly trend of the Great Rift at Craters of the Moon National Monument (Stearns, 1963); the trend of a related rift that passes through King's Bowl (near SW. cor. sec. 29, T. 5 S., R. 28 E., about 19 miles west of Aberdeen; see Prinz, 1967, 1970); and the observed alignments of lava vents in the Snake River Plain (Stone, 1969). My confidence in a lack of faulting along the principal lineament is reinforced by my interpretation that the lineament is related solely to a peculiar (and still inexplicable) distribution of surficial sand, which survives precariously, as I will now explain.

The blanket of sand in which ryegrass grows along the principal lineament, as well as the patches of sand that support the variegated vegetation west of the lineament, overlies at many places a relic calcareous hardpan (unit 3 of the section on page 129), but the sand also rests locally on basalt. The sand is therefore unconformable on a terrain that was formerly more continuously covered by this hardpan. (A similar remark applies to the friable silt layer, unit 2 of the section on page 129, which also truncates the calcareous hardpan.) As the youngest deposit in the local landscape, the blanket of sand along the lineament can hardly be considered as geologically immobile. It is indeed only loosely held by the ryegrass and has no identifiable weathering features indicative of stability.

The scalloped boundary of sand observed along the eastern edge of the principal lineament demonstrates that some of the sand migrates from time to time northeast. It seems likely that considerable sand has been removed from the patchy area of mixed vegetation west of the lineament and that this area is still in process of recovering vegetational equilibrium. Some of the sand that previously blanketed the area west of the lineament is almost surely incorporated in the belt of sand described above (p. 121) as following a parallel northward trend 3 miles east after emanating from the lineament. At the terminus of this younger belt of sand, in the west half of sec. 12, T. 5 N., R. 33 E., the belt is crossed by several streaks of sand, which are part of an extensive tract of active longitudinal dunes that trend about N. 50°E. across the Mud Lake area, concordant with the present direction of prevailing winds. Thus, three bodies of sand of decreasing age are recognizable: a partly eradicated blanket of sand along the principal lineament; a younger belt of drifting sand parallel with the lineament a few miles east; and northeasterly longitudinal dunes near Mud Lake. Despite the differences in age, all these deposits of sand are more or less mobile and are geologically young.

According to the geologic relations just described, the principal lineament is only one of several features intimately linked with the action of wind. It defines the east edge of remnants of an eroded blanket of sand that apparently represents a former wind deposit. Although the direction of the lineament differs from the present trend of prevailing winds, the trend of the belt of sand of intermediate age (which undoubtedly represents a pattern produced by wind) parallels the principal lineament. By this analogy, the trend of the lineament is probably also a result of former winds. The analogy is strengthened by at least one other curious similarity: the southern ends of both the lineament and the younger belt curve northward from initial paths that trend northeast. In short, the principal lineament and the parallel belt of drifting sand on the east apparently express the same geologic agent (wind) and have only slight individual distinctions that reflect a small difference in geologic age.

Age

The maximum age of the principal lineament is, of course, limited by the age of the basalt below. This lava crops out at many places and accurately exhibits the complex surface features of volcanic terrain, as is typical of other lavas of the late Pleistocene Snake River Group (Malde, 1965). Close inspection, however, shows that the original glassy skins on surfaces of ropy lava have been largely destroyed and that the vesicular upper part of the basalt in most places is exfoliating in thin shells. In my judgement, the degree of weathering indicated by these changes exceeds the rudimentary surface alteration seen on a lava flow older than the Bonneville Flood (30,000 years) near King Hill, Idaho (Malde, 1971).

The limit of age for the principal lineament can be further estimated from characteristics of the calcareous hardpan on the basalt. The thickness and intensity of carbonate in this hardpan corresponds with these attributes of the carbonate horizon in soils of this region on deposits at least 30,000 years old (p. 38). Properties of the hardpan are therefore compatible with the age estimated from weathering of the basalt. The age of the friable silt, which is unconformable on the hardpan, cannot be closely estimated. The surficial blanket of sand, however, lacks a recognizable soil profile and must be geologically young. By comparison with the degree of soil formation found on other surficial deposits in the region, such as the soil on alluvial fans considered to be less than 4,000 years old near Arco (p. 36), the blanket of sand that identifies the principal lineament is probably only a few hundred years old--perhaps only a few decades.

Summary and predicted future behavior

The principal lineament, extending 17 miles N. 10°E. on the lava plain from sec. 11, T. 2 N., R. 32 E., to sec. 21, T. 5 N., R. 33 E., is expressed by an abrupt boundary between contrasting vegetation and surficial deposits: drab sagebrush growing in silt on the east; and a mixed stand of ryegrass, rabbit brush, thistles, prickly pear, and relatively sparse sagebrush rooted in patches of loose sand on the west. At many places, narrow streaks of ryegrass supported by loose sand a foot or two thick lie along the boundary and mark the lineament. Numerous initial volcanic forms typical of lava terrain pass beneath the lineament without change, and the lineament is evidently a surficial feature superimposed on the lava plain. Traced along its length, the lineament crosses many well-exposed lava outcrops, none of which are visibly faulted. This finding is further confirmed by an excavation dug to the unbroken lava surface in a smooth area thinly mantled by surficial deposits.

The origin of the principal lineament is still elusive, but it appears to mark the east edge of remnants of the oldest of several contiguous deposits of surficial sand that express the action of wind. A younger belt of more or less actively drifting sand a few miles east has the same trend, shape, and approximate dimensions. This trend, however, differs from the present direction of prevailing winds, which is N. 50°E.

Basalt below these surficial deposits has features of surface weathering that indicate an age exceeding 30,000 years, by comparison with weathering on a lava flow of known age along the Snake River. Calcareous hardpan that represents ancient soil formation on the lava plain is compatible with this age assignment. The sand that distinguishes the lineament is not yet stablized by soil formation, and the lineament is accordingly less than 4,000 years old. More closely estimated, the age of the lineament is probably only a few hundred years old--perhaps only a few decades.

If the origin of the principal lineament has been correctly interpreted as a geologically ephemeral effect of wind, the remnants of sand will be eventually obliterated, the uniformity of sagebrush will be restored, and the lineament will be thereby effaced.

Lineaments near the EBR-II site

Two lineaments parallel to the principal lineament and about a mile west, one of which passes through the site of the Experimental Breeder Reactor II (EBR-II), were also investigated by study of surface features and by trenching (fig. 20). In all visible characteristics,

Figure 20.--NEAR HERE.

except length, these lineaments are analogous to the principal lineament. They are marked chiefly by more or less continuous bands of ryegrass rooted in loose sand, which reach as far as any individual streak of ryegrass by which the principal lineament is mainly recognized. The lineament that passes through the EBR-II site is about 3 miles long (from the center SW 1/4 sec. 12, T. 3 N., R. 32 E., to the center SE 1/4 sec. 26, T. 3 N., R. 32 E.), and its companion lineament 1,000 feet west measures a little more than a mile (from the north boundary of sec. 26, T. 3 N., R. 32 E., southward a short distance into sec. 35). Such bands of ryegrass, like those along the principal lineament, have fairly regular western boundaries, whereas the eastern edges are ragged and scalloped, by reason of lobes of sand that extend a few tens of feet northeast. Each of these lineaments is further defined, especially near their southern limits, by tall sagebrush 3-4 feet high that determines a dark-toned band as much as 500 feet wide with abrupt boundaries to the west and east of the central streak of ryegrass. Sagebrush that flourishes in this way is also conspicuous along some stretches of the principal lineament. Both lineaments terminate abruptly at the south where they are truncated diagonally by a dark streak, which belongs to a tract of northeasterly lineaments that are described later in this report (p. 146).

Figure 20.--Vertical view of lineament that passes through the EBR-II site about 1 mile west of the principal lineament, showing the position of trenches excavated for study of the concealed basalt surface and its overlying surficial deposits. The north end of a companion lineament about 1,000 feet west is at the southwest corner. The area covered by this photograph is outlined on figure 1. (From Idaho Operations Office aerial photograph 16-570 taken October 1949.) North is at top of page. Scale is approximate.

The lineaments near the EBR-II site cross various lava outcrops, none of which show signs of faults. Pressure ridges are commonly seen that extend unbroken across these lineaments. A shallow stream bed near the northeast corner of sec. 26, T. 3 N., R. 32 E., that pursues a winding course across both lineaments, provides almost continuous exposures of the underlying unbroken basalt surface. Another stream bed near the south boundary of sec. 26 crosses the western lineament and exposes a continuous unbroken lava outcrop on its floor.

To further test for continuity of basalt beneath the lineaments, a trench was dug to the concealed basalt surface across the band of ryegrass that identifies the lineament 1,000 feet south of the EBR-II site (fig. 21). This trench reveals that the basalt has a fairly

Figure 21.--NEAR HERE.

regular surface throughout most of the distance across the lineament, at a depth ranging from 3 to 4 feet, but the basalt near the west edge of the lineament rises to a gentle pressure ridge that is fractured on the west limb. Cracks of this kind that extend short distances along pressure ridges commonly form during initial flowage of the lava by local heaving of the solidified crust as it floats on liquid lava below, and such cracks are virtually universal on lava terrain of this region. Cracks in pressure ridges of a lava flow have no relation whatever to faulting. In short, the trench near the EBR-II site is as devoid of evidence of faults as is the trench on the principal lineament.

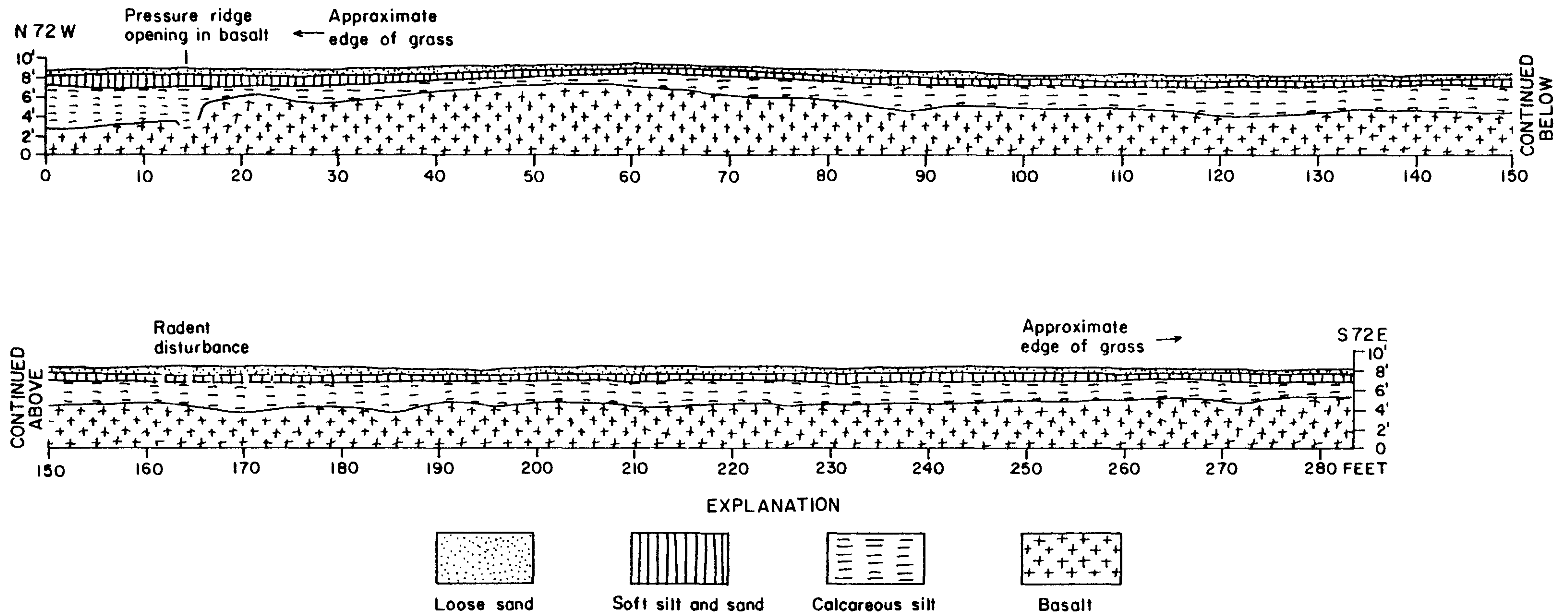

Figure 21.--Profile sketch of surficial deposits on basalt exposed by trenching across the lineament 1,000 feet south of the EBR-II site.

Ryegrass along the lineaments near the EBR-II site grows in loose sand, as it does along the principal lineament. Surficial deposits below the sand, including a hardpan on the basalt, are substantially identical to the deposits distinguished at the principal lineament (p. 129) and need no further description here. The conclusions about origin and age for the principal lineament apply with equal force to the lineaments near the EBR-II site, namely that these lineaments are sandy features of wind action probably not more than a few hundred years old that have no demonstrable relation to faulting.

Dark lineaments near Middle Butte

General relations

Aerial photographs of the lava plain northeast of Middle Butte show a series of subparallel dark streaks that trend generally northeasterly along distances of several miles (fig. 22). These

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Figure 22.--NEAR HERE.

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lineaments cross stream beds of an immature dendritic drainage system that has developed on this area of the lava plain, and they are obviously surficial features. Although an explanation for these dark lineaments is still problematical, they have been traced out on foot and studied by trenching without finding associated evidence of identifiable faults. Indeed, all the observable geologic relations point to recent origin by some process that has operated only at the surface (probably wind action), thereby producing a distinctive vegetation pattern. As discussed below, the vegetation that accounts for the dark streaks is abnormally tall sagebrush.

The dark lineaments are so uniform from the air that each of them surely represents the same phenomenon. A typical streak is no more than 50 feet wide and is commonly much narrower. The directions of the lineaments, however, are far from uniform. In the southern part of this tract they trend more or less directly away from Middle Butte, N. 55°-60° E. In the northern part, the trend swings progressively northward to a direction N. 20°E., again radial from Middle Butte.

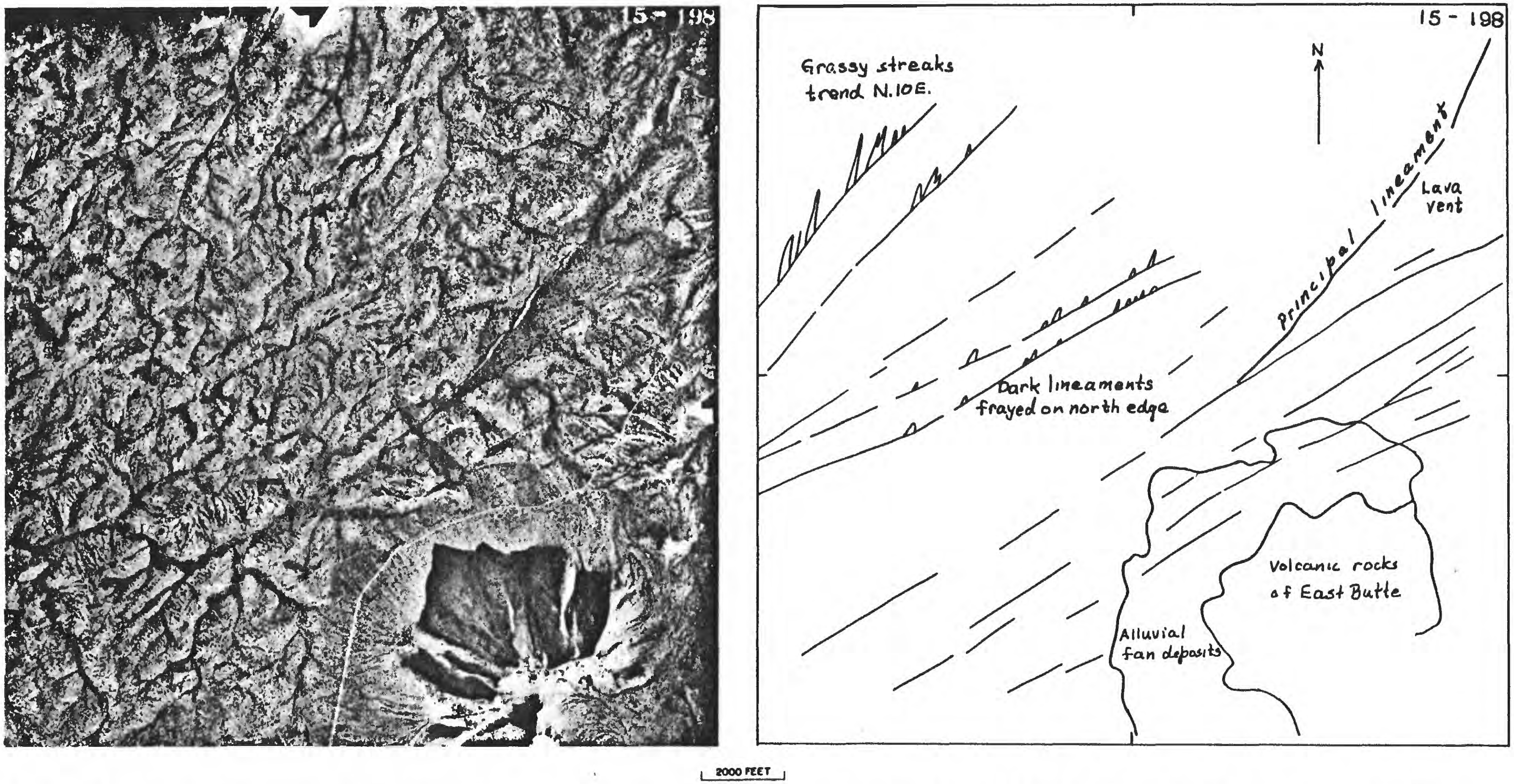

Figure 22.--Vertical aerial photograph of part of a tract northeast of Middle Butte marked by dark linear streaks that trend northeasterly. Various features are indicated on the accompanying sketch. The area covered by the photograph is outlined on figure 1. (From Idaho Operations Office aerial photograph 15-198 taken October 1949. Scale is approximate.

A curious attribute of the dark lineaments, which is especially noticeable in the northern part of this tract, is that the south edge of a dark lineament is extraordinarily sharp, whereas the north edge is frayed. This effect attains its most conspicuous expression in lineaments that connect (or intercept) short closely spaced dark patches that taper northward at an acute angle, thus producing the appearance of a feather stripped of barbs on one side (see sec. 4, T. 2 N., R. 32 E., in northwest part of fig. 22). Such subsidiary streaks that are linked with a dark lineament trend rather uniformly N. 10°E., and many of the larger ones are further marked by medial bands of ryegrass rooted in loose sand. These short bands of ryegrass, which are associated with dark-toned vegetation, are identical in appearance (and in direction) with the principal lineament as well as with the lineaments near the EBR-II site. Indeed, the lineaments near EBR-II are the longest of many bands of ryegrass in the north part of this tract that terminate where crossed diagonally by a dark lineament. The possible significance of these relations in understanding the origin of the northeasterly dark lineaments is interpreted below (p. 157).

At ground level, the dark lineaments are distinguished by sagebrush that grows about 4 feet tall (fig. 23). Sagebrush in the

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Figure 23 .--NEAR HERE.

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adjacent plain ordinarily grows with equal density but only 1-2 feet high. The tall sagebrush along these lineaments casts comparatively large shadows and causes the streaks to appear dark from the air. In places along a lineament, but not universally, the tall sagebrush coincides with a very subdued ridge of silt and sand that rises not more than a foot above the surrounding plain.

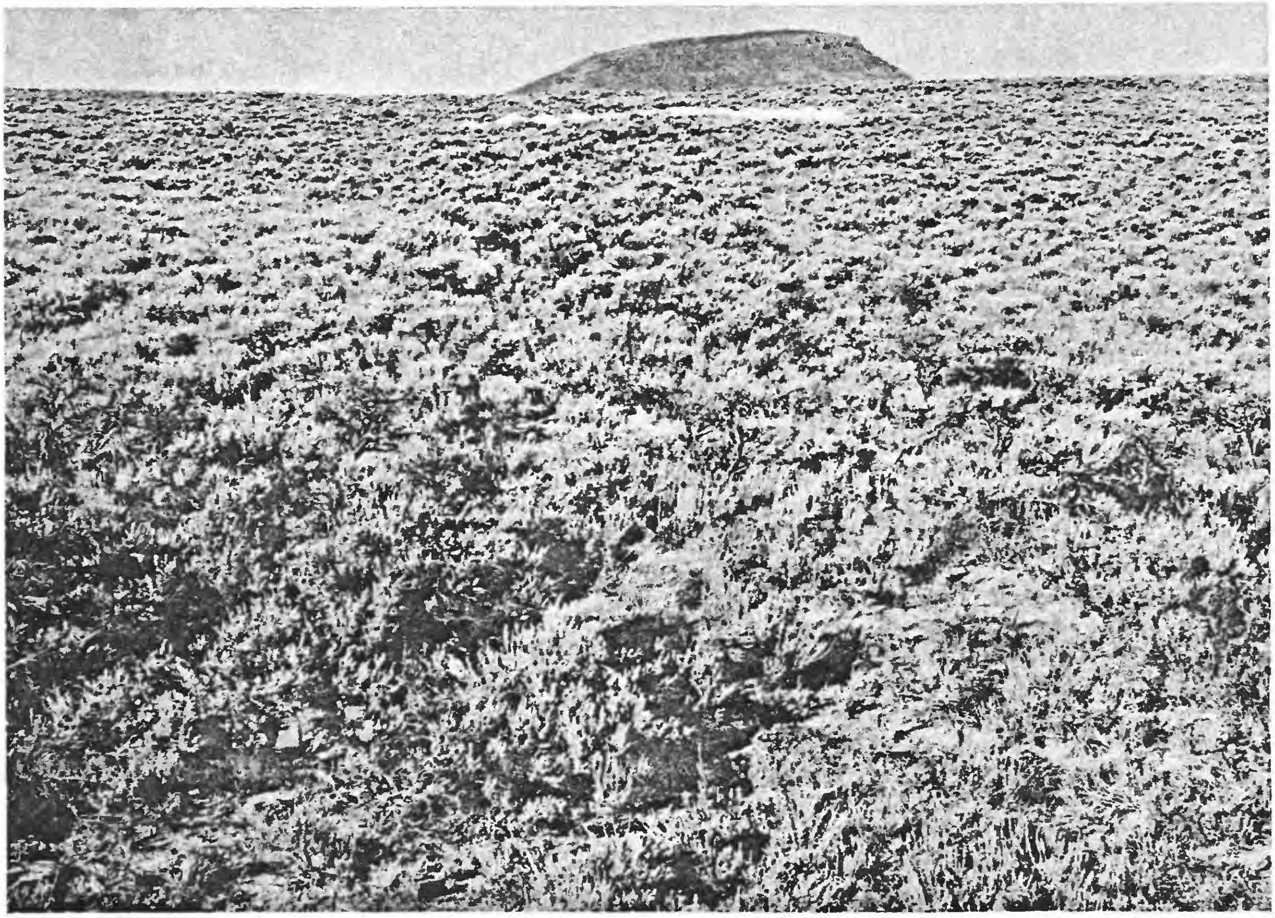

Figure 23.--Photograph toward Middle Butte from a position on a dark lineament. Tall sagebrush along the lineament casts comparatively strong shadows. Earth excavated from a trench across the lineament is visible in the middle distance. This lineament is near the south boundary of sec. 1, T. 2 N., R. 32 E.

Traced along the ground, the dark lineaments encounter relatively few lava outcrops because of a prevalent thick blanket of silt. The lineaments nonetheless cross a diversity of local relief by transversing numerous valleys of the drainage network found in this area, even though the lineaments are not necessarily visible on the floors of all such valleys. The depth of the larger valleys exceeds the average thickness of the surficial silt as well as the relief typical of lava flows, and it is clear that these valleys are incised into the local basalt. The dark lineaments therefore occur on silt that mantles a dissected lava plain. By this evidence, the dark lineaments are to be counted among the youngest features of the landscape . Interestingly, three of the dark lineaments are recognizable on alluvial fan deposits on the north flank of East Butte (fig. 22), and this circumstance also supports a young geologic age for the lineaments. The lava outcrops that are infrequently intersected by a lineament are mainly coherent surfaces of pressure ridges. Gaps, of course, exist in the lineaments at such outcrops.

Features exposed by excavation

Because basalt outcrops are scarce along these northeasterly lineaments, trenches perpendicular to a dark lineament were excavated at three sites, two of which reached the concealed basalt surface (fig. 24). These trenches also provided an opportunity to examine

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Figure 24.--NEAR HERE.

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the surficial deposits above the basalt, in the hope of finding characteristics that might account for the tall sagebrush that flourishes along the dark lineaments. These trenches show that neither the basalt nor the surficial deposits is broken by faults. The basalt lies at variable depth, more than 12 feet at one site, and the basalt has no discernible linear irregularities that coincide with the lineament. Features of the surficial deposits, however, are frustrating in that they fail to indicate any consistent attribute that accounts for the tall sagebrush. The surficial deposits are nonetheless useful, showing that the basalt is comparatively old and that the dark lineaments are correspondingly young.

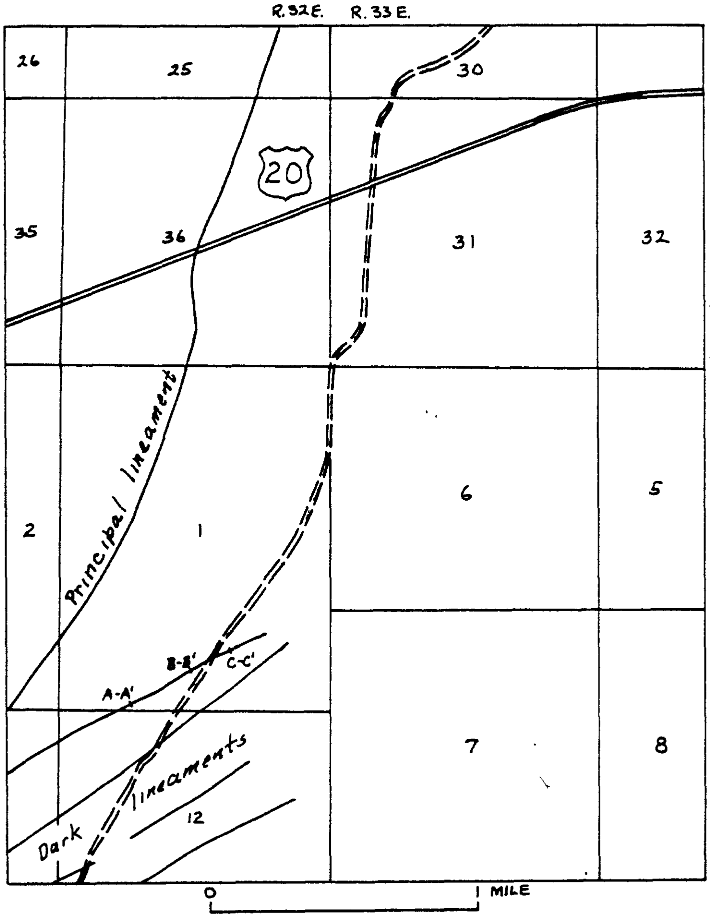

Figure 24.--Sketch map showing location of trenches across dark lineament near East Butte.

At trench A-A' (fig. 25), the basalt forms a slightly uneven

Figure 25.--NEAR HERE.

surface at a depth of about 7 feet. The ground surface rises slightly (less than a foot) in the part marked by tall sagebrush, but this extremely subdued topography does not conform with any recognizable boundary in the surficial deposits. Indeed, the various layers of surficial material are virtually uniform across the lineament. Below a surface layer of friable silt and sand 0.7 foot thick, is about 3 feet of calcareous hardpan comparable to the hardpan on basalt at the principal lineament and at the lineament that passes through the EBR-II site. This hardpan rests abruptly on a lower hardpan of similar character that continues downward to the basalt. Along the contact between the hardpan layers are scattered fragments of basalt as large as cobbles, which express the familiar feature known to soil scientists as "stone lines." Such a line of stones of course represents a layer of stones scattered on a former land surface, much like stones that litter some parts of the present landscape, and the stone line therefore indicates an ancient pause in the buildup of surficial silt. The favored explanation for stone lines is that they require running water for their transport (Ruhe, 1959), and their presence therefore signifies some erosion.

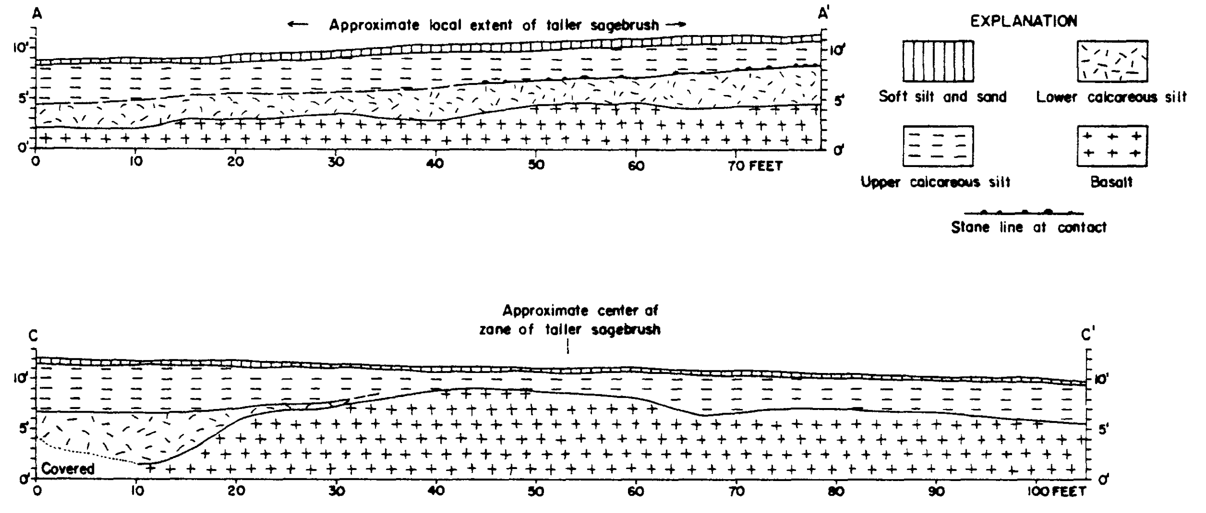

Figure 25.--Profile sketches of surficial deposits on basalt at trenches A-A' and C-C', perpendicular to a dark lineament near East Butte.

Trench B-B' was excavated to a depth of 12 feet but reached basalt only at one end. Hardpan layers exposed in surficial deposits cut by this trench closely resemble the two hardpans found at trench A-A', but the upper hardpan in trench B-B' rises about a foot in a subdued arch beneath tall sagebrush of the lineament. This is the only change in surficial deposits found thus far that coincides with the dark lineament. This feature suggests that tall sagebrush along the dark lineaments may be related to the occurrence of calcareous hardpan close to the surface, even though no such correspondence is apparent at the other trenches.

At trench C-C' (fig. 25), basalt below the surficial deposits forms a pressure ridge with 8 feet of relief. The vesicular lava surface is continuous on this ridge. Curiously, the ridge corresponds with the position of the lineament, but I consider this circumstance to be fortuitous. Where the basalt is deeply buried on the flank of the pressure ridge, two hardpan layers are present, as in the other trenches. From the absence of the lower hardpan on the ridge crest, it appears that this site was somewhat eroded before the upper hardpan was formed. The general sequence therefore matches that expressed at trench A-A', where a stone line representing an indeterminate amount of erosion marks the contact between the lower and upper hardpan layers.

Origin and age

The only attribute of the dark lineaments that is at all helpful in comprehending their origin, in addition to their obvious surficial character, is the relation of the dark lineaments to north-trending grassy streaks allied with the principal lineament (p. 148). The pattern of diagonal intersections of dark lineaments with the grassy streaks suggests that a set of sandy north-trending lineaments has been largely obliterated by the process that formed the dark lineaments, such as might be accomplished by dragging the teeth of a gigantic rake across the landscape. The pattern clearly could not form by a process that moved northward over the dark lineaments because no source for the sand found along the grassy streaks would then be available. In short, the dark lineaments have modified the grassy streaks and are undoubtedly younger. The sharp edges of the dark lineaments, where they cut across the grassy streaks, are a feature of many wind-swept areas in which deflation of surficial deposits commonly produces abrupt linear boundaries. Deflation by wind, for example, adequately explains subparallel scarps in surficial silt in southwest Colorado (Shawe, 1963), which were previously considered to be fractures. I therefore favor, but cannot prove, the interpretation that the dark lineaments represent the effect of wind scour in a northeasterly direction across north-trending streaks of sand of which the principal lineament and the lineaments near the EBR-II site are the major remnants. The radial trend of the dark lineaments with respect to Middle Butte suggests that this topographic prominence may have influenced the direction of local winds.

Tall sagebrush along the dark lineaments, as well as sagebrush on remnants of the north-trending lineaments that extend like barbs on a feather, implies that enough surficial sand remains to hold the soil moisture needed for flourishing growth, even though surficial sand is not conspicuously thick in the trenches that were excavated.

Unbroken hardpan layers below the dark lineaments, by analogy with comparable hardpan below the principal lineament, indicate an age for the dark lineaments not greater than 30,000 years. If the pattern of these dark streaks with respect to the north-trending lineaments is correctly understood, then the dark northeasterly lineaments are younger than the principal lineament and are accordingly not more than a few hundred years old. The presence of the dark lineaments on undissected alluvial fans at East Butte, which are being built by contemporary runoff, supports this young geologic age. The dark lineaments are nonetheless obscured on the floors of some valleys, apparently by deposition of alluvium, and it is likely that wind action is no longer dominant over stream transport in this part of the lava plain.

In summary, observable features of the dark northeasterly lineaments favors their origin by wind scour in modern times, subsequent to the formation of the principal lineament and the lineaments near the EBR-II site. Evidence for faulting is wholly lacking along these dark lineaments.

Microearthquake studies

by

A. M. Pitt and J. P. Eaton

The National Center for Earthquake Research of the U.S. Geological Survey made a 9-month study of microearthquakes in the area of the NRTS. The purpose of the microearthquake study was to determine whether the faults near the NRTS identified by Bonilla and Chase, or perhaps other faults that are less well marked by surface features, are sources of microearthquakes. If recorded in sufficient numbers, microearthquakes could be used to delineate the structures on which they originate and, in conjunction with geologic evidence, reveal the forces and processes that are currently acting within the earth's crust in the vicinity of the NRTS.

A six-station telemetered seismic network was installed on and immediately north of the NRTS in December 1968, and it was operated until September 1969 (fig. 26). The net consisted of five stations with short-period vertical-component seismometers and one station with both vertical- and horizontal-component seismometers. Seismic signals were transmitted to the NCER in Menlo Park, California, via Federal Telecommunications System phone lines. Because these lines were unavailable during normal working hours, the net was in operation only at nights and on weekends--between 12 and 15 hours per day on the average.

Figure 26.--In pocket.

The network and recording equipment, the data reduction procedures, and the computer programs utilized in analysis of the data had been previously developed and tested at the NCER for use with the California San Andreas fault research network, which has received support from the AEC's Division of Reactor Development and Technology. The equipment and data analysis procedures have been described by Eaton, Pakiser, and Lee (1971).

The NRTS network was designed to yield good epicenters and approximate focal depths of microearthquakes on or just north of the NRTS. If active spots were found within this region, minor readjustment of the network would enable it to determine reliably the focal depths in particular areas. The network also was designed to provide a basis for calculating the approximate epicenters of events well outside of the network. Stations of the USGS Yellowstone-Hebgen Lake network about 200 km northeast of the NRTS provided additional data on earthquakes originating north, northeast, and east of the NRTS net. Some of the larger earthquakes were also recorded on the AEC/USGS microearthquake network near Hanford, Washington.

The NRTS network was sufficiently sensitive to record earthquakes as small as magnitude 1 up to distances of 100 km from the net; earthquakes as small as magnitude 0 within the net should have been detectable.

During the 9-month period of operation, the NRTS network did not locate a single earthquake within 70 km of the center of the net. No seismic activity was detected in the vicinity of the Arco and Howe fault scarps north of the NRTS or on the site itself. Moderate activity, however, was detected in two zones that pass within about 100 km of the NRTS. Both of these zones are important elements in the pattern of major active tectonism in the western U.S. and show up clearly on the Worldwide Seismicity Maps for 1961-1967 compiled by Barazangi and Dorman (1969). The more important one is the major seismic zone along the eastern border of the Basin and Range province, which extends northward along the Idaho-Wyoming border (east of NRTS) and into western Montana. The magnitude 7.1 Hebgen Lake earthquake of August 17, 1959, occurred in this zone about 150 km northeast of the NRTS. The second active zone runs from the Yellowstone area west-southwestward through the mountainous region near the Snake River Plain north of the NRTS.

Locations of seismographs for the NRTS and Yellowstone nets and epicenters of earthquakes near the NRTS from December 10, 1968, to June 30, 1969, are shown in figure 26. Data on the earthquakes are presented in table 4. Techniques for determining magnitudes for small earthquakes recorded on short-period electromagnetic seismographs of the kind in the NRTS net are not well developed, and the magnitudes assigned in table 4 may be as much as 1 unit below the standard Richter M_L.

If large numbers of microearthquakes had been detected in the vicinity of the NRTS, they would have been very helpful in delineating active, currently moving, faults in the region. Their absence during a fairly short recording interval, however, does not disprove the possibility that the crust in this region contains and is now

Table 4.—*Data on earthquakes near the NRTS from December 10, 1968 to June 30, 1969*

Note: Relative evaluetion ie based upon the quality of P and S arrivals, the distribution of statione, the number of etatione available, and the P-arrival time reeiduals at the etations used to determine the epicenter. The letters indicate the following maximum probable epicentral errors: A - 10 km, B - 15 km, C - 30 km.

Number	Date	Origin Time (GMT) hr min	sec	Latitude °	'	Longitude °	'	Magnitude	Relative Evaluetion	Remarks
	Dec. 68									
1	30	01 51	19.2	43	49.8	114	26.4	-	B	
	Jan. 69									
2	1	04 07	21.1	44	44.0	111	22.7	-	B	
3	1	08 33	27.9	43	54.6	114	17.4	-	A	
4	18	16 31	03.1	43	57.3	114	30.9	1.0	A	
5	20	05 02	31.9	44	09.5	114	25.9	1.1	C	
6	21	12 16	37.9	44	41.4	113	01.2	1.7	A	
7	23	09 55	02.4	44	38.2	111	19.7	-	B	
8	24	10 28	00.3	43	52.7	114	22.9	0.9	B	
9	24	10 40	58.9	44	31.7	111	30.0	1.1	B	
10	25	15 40	17.4	44	42.9	110	35.2	2.1	C	
11	26	02 19	02.5	44	45.7	110	33.7	-	C	
	Feb. 69									
12	3	00 14	05.0	44	38.5	113	03.7	0.8	A	
13	3	00 56	10.9	44	35.0	113	01.3	1.6	A	
14	3	00 59	21.0	44	37.0	113	04.2	0.7	A	
15	3	12 46	05.9	44	37.7	113	01.9	0.8	A	
16	6	04 53	44.6	43	46.3	111	07.3	1.5	B	
17	10	03 05	14.6	43	12.5	111	30.7	0.6	B	
18	11	03 33	42.8	43	50.7	111	12.5	1.7	B	
19	15	00 28	20.5	44	52.1	111	44.1	-	B	
20	15	08 57	57.9	44	40.2	111	11.9	1.4	B	
21	20	02 34	02.0	42	42.6	111	34.1	-	C	
22	20	06 36	28.6	44	00.6	114	35.4	1.2	C	
23	21	17 11	16.3	44	35.7	111	32.0	2.3	B	
24	25	02 46	35.8	43	14.8	111	12.1	1.6	C	
25	28	05 57	56.8	44	45.7	111	40.2	1.2	C	
	Mar. 69									
26	1	21 38	31.9	42	39.3	111	10.0	1.6	C	
27	8	08 26	17.3	44	40.4	111	40.0	2.3	C	Magnitude 4.1 by USC&GS

Table 4.--*Data on earthquakes near the NRTS from December 10, 1968 to June 30, 1969*--Continued

Number	Date	Origin Time (GMT) hr min	sec	Latitude °	'	Longitude °	'	Magnitude	Relative Evaluation	Remarks
	Apr. 69									
28	1	03 50	43.5	44	59.8	113	00.2	2.2	C	
29	5	02 15	13.0	44	32.4	112	07.9	0.8	B	
30	5	08 56	27.5	43	14.4	110	16.7	1.3	C	
31	5	10 56	29.4	42	59.4	110	52.1	1.7	C	
32	6	19 46	01.9	44	45.7	110	56.1	2.1	A	
33	10	09 33	01.7	44	43.2	110	36.3	2.2	C	
34	12	01 00	23.8	43	54.1	114	04.9	-	C	
35	13	06 19	18.5	44	42.3	111	37.0	2.1	C	
36	17	13 06	01.1	44	44.7	111	02.0	1.7	B	
37	22	13 23	58.7	43	54.6	114	36.8	-	C	Magnitude 3.6 by USC&GS
38	27	07 03	06.5	44	40.9	110	58.8	1.6	B	
39	27	07 21	35.4	44	38.4	110	49.9	1.8	C	
40	27	08 18	52.9	44	34.3	110	43.5	2.2	C	
41	27	10 50	09.6	44	33.8	110	44.5	2.5	C	
42	27	21 31	28.6	43	55.7	114	35.0	-	B	Magnitude 3.7 by USC&GS
	May 69									
43	3	09 58	27.3	45	11.4	111	39.5	1.6	B	
44	3	10 17	07.3	44	09.1	114	32.5	1.8	A	
45	5	07 09	08.6	43	54.5	114	34.0	-	B	Magnitude 4.6 by USC&GS
46	12	01 09	45.4	45	11.7	111	35.4	2.2	B	
47	16	02 11	14.7	44	00.2	114	34.4	2.1	C	
48	22	03 56	18.3	44	07.8	114	29.8	2.1	B	
49	31	02 24	27.7	44	06.6	114	31.4	-	B	Magnitude 3.3 by USC&GS
	Jun. 69									
50	3	06 01	55.0	43	58.1	114	35.2	-	C	Magnitude 3.7 by USC&GS
51	7	13 42	26.2	44	22.8	112	54.3	1.5	C	
52	8	09 56	25.9	44	08.4	114	25.3	-	C	

accumulating stored elastic strain that might be released suddenly, by slippage on a fault that is now quiet, thus generating a large earthquake. Such appears to be the situation along the San Andreas fault in California southeast of Cholame. Although one of California's largest earthquakes occurred on that section of the fault in 1857, and geologic evidence shows that the fault has slipped there many times in the recent past, the level of microearthquake activity in that region is extremely low at the present time.

Lacking clear evidence to the contrary, it must be assumed that earthquakes as large as the 1959 Hebgen Lake earthquake (magnitude 7 to 7 1/4, say) might occur anywhere in the active zones near the Snake River Plain on the east, north, and northwest. Estimates of the probable maximum size of earthquakes that can be expected on known faults in this region can be deduced more accurately from the detailed geologic studies of this report than from this short-term study of microearthquakes.

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