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GEOLOGIC FEATURES OF THE EARTHQUAKE AT HEBGEN LAKE, MONTANA, AUGUST 17, 1959

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ABSTRACT

In the epicentral region of the Hebgen Lake earthquake, Montana, late Cenozoic structures marked by tension are superimposed on Laramide structures marked by compression. During the earthquake, several large normal faults northeast of Hebgen Lake, and many small faults and monoclines south of it, were reactivated, and a very large area was abruptly dropped and warped.

New fault scarps are as high as 20 feet. They are mostly in unconsolidated or weakly coherent material but certainly reflect displacements of the underlying bedrock. Offsets produced by refraction of faults, which are steeper in surficial material than in bedrock, and by various types of slumping, generally result in surficial scarps higher than true fault displacements.

Subsidence amounted to as much as 22 feet in the lake basin, as proved by releveling of bench marks by the Coast and Geodetic Survey and by shoreline measurements around Hebgen Lake. Parts of the basin subsided differentially, warping the lake bed and creating a gigantic long-lived seiche. Depth-sounding traverses of the lake recorded warping but gave no indication of major faulting of the lake bottom.

A part of the Madison Valley, west of Hebgen Lake, also subsided, though not as much, and a segment of the Madison Range fault was reactivated. At least part of the highway through Madison River Canyon, which cuts directly across the Madison Range between Hebgen Lake and Madison Valley, subsided also; one group of geologists regards this subsidence as tectonic, and considers the entire range, for which there are otherwise no positive data, to have subsided between Hebgen Lake and Madison Valley. In this view, an eastward trending syncline has been propagated across the northwest-trending Madison Range. Another group considers the subsidence in Madison River Canyon to be due in part to compaction and slumping, and the Madison Range to have changed little in altitude. The pattern of deformation appears to them as the uneven subsidence of two northwest-trending basins, one on either side of the Madison Range.

The earthquake caused widespread slumping and sliding of the surficial mantle; the huge Madison Slide killed 26 people. An old earthflow was reactivated and moved 100 feet or more in the month following the earthquake.

Introduction

On August 17, 1959, at about 11:37 p.m., MST (6:37 a.m., August 18, GCT) southwestern Montana and adjacent areas were shaken by a major earthquake. The shock had a magnitude of 7.1 (Pasadena), and was felt over an area of 600,000 square miles, being noted as far as 550 miles from the epicenter near Hebgen Lake (fig. 1).* Several large new fault scarps and many smaller ones were formed, and a very large area was abruptly dropped and warped. The surficial mantle slumped and slid extensively.

Two field parties of the Geological Survey were in the region at the time. They were joined soon afterward by other Survey personnel for a detailed investigation of the effects of the earthquake and their relation to the geologic history of the region. This study was made with the invaluable cooperation of the Bureau of Public Roads, U.S. Coast and Geodetic Survey, U.S. Forest Service, National Park Service, and the Montana Power Company.

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* Figure 1 is in rear pocket.

A comprehensive report on geologic, seismic, and hydrologic aspects of the Hebgen Lake earthquake will be published by the U.S. Geological Survey. The present paper is a condensation, prepared largely by Nancy C. Pearre, of chapters from that report, written separately or jointly by George D. Fraser, Jarvis B. Hadley, Warren Hamilton, Wayne H. Jackson, W. Bradley Myers, Willis H. Nelson, Gerald M. Richmond, and Irving J. Witkind. Photographs are by John R. Stacy.

STRUCTURAL SETTING

The deformation that accompanied the 1959 earthquake took place in a complex structural setting in which middle and late Cenozoic normal faults, forming block ranges and basins, have been superimposed upon Laramide (Late Cretaceous to Eocene) overturned folds and thrust faults. The conspicuous tectonic elements of the epicentral area (fig. 1) trend northwestward. On the west is Madison Valley, an intermontane basin 55 miles long and 5 to 12 miles wide. The valley is bounded on the east by the high, fault-block Madison Range; the fault zone at the foot of the range is marked in places by a Recent fault scarp 20 to 40 feet high. The east part of the range gives way southeastward to the broad West Yellowstone basin, within which lies Hebgen Lake. Madison Valley is the dropped core of Precambrian crystalline rocks of a Laramide uplift; Madison Range exposes the flank of the uplift, in which the Precambrian rocks are thrust northeastward over a belt of folded and faulted rocks of Paleozoic and Mesozoic age, and which in turn is bounded on the northeast by an area of broadly arched structures and minor high-angle faults.

Southwest of the epicentral area, the Centennial Mountains and Centennial Valley trend easterly, dwindling out as cross structures deforming the southern part of Madison Valley. The mountains are bounded on the north by the Centennial fault zone, which has been active in Pleistocene and Recent time.

Toward the east, southeast, and south, the late Cenozoic tectonic elements lose structural relief and vanish in the young volcanic rocks of the Yellowstone Plateau and the Snake River Plain.

A broad depositional plain of obsidian sand and gravel extends from the Yellowstone Plateau to the Madison Range, forming most of the surface of the West Yellowstone basin. This plain, which slopes gently northwestward, has been tilted and warped as a result of recurrent subsidence of the West Yellowstone basin, and has been deformed in detail by repeated movement on small faults and monoclines south of the lake.

DEFORMATION ACCOMPANYING THE EARTHQUAKE

The major new fault scarps formed along pre-existing normal faults northeast of Hebgen Lake (fig. 1). The reactivated faults are expressed both as spectacular scarps as much as 20 feet high in unconsolidated material (figs. 2 and 3) and as gaping clefts with little or no displacement. Each fault scarp is paralleled by many smaller scarps and related fissures, most of which are in the unconsolidated material of the hanging wall rather than in the footwall.

The main scarps face and dip south or southwest toward the West Yellowstone basin. That the ground south of the faults subsided, rather than that the ground north of the faults rose, was proved by the U.S. Coast and Geodetic Survey. The West Yellowstone basin, the Madison River Canyon, and the lower Madison Valley are traversed by a line of second-order leveling run by the Coast and Geodetic Survey in 1934. This line was rerun by the Coast and Geodetic Survey to first-order standards after the earthquake. Along a 32-mile portion of the line, 47 bench marks, all but one of those recovered, subsided more than 0.5 foot.

Subsidence was proved over much of an area nearly 15 miles north-south and almost twice as long east-west. The maximum subsidence was 22 feet in the Hebgen Lake basin. About 50 square miles subsided more than 10 feet, and something like 200 square miles subsided more than 1 foot. Only about half a foot of absolute elevation was proved.

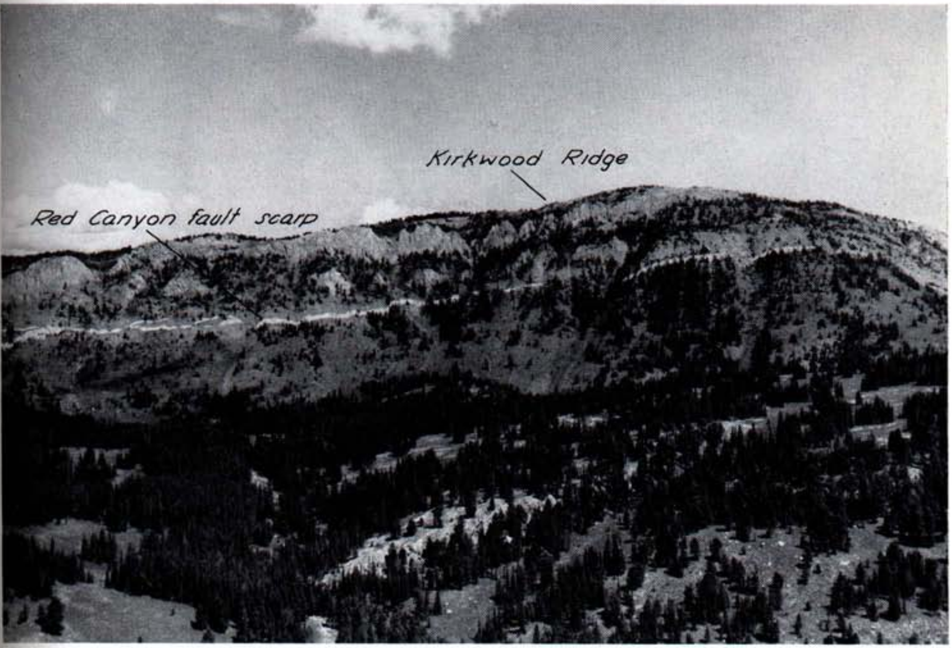

FIG. 2. Red Canyon fault scarp as exposed along south flank of Kirkwood Ridge.

Many small faults in the West Yellowstone basin were also reactivated, and the entire obsidian-sand plain was tilted gently northward. West of the Madison Range, a part of the Madison Valley along the latitude of Hebgen Lake subsided, though not as much as the Hebgen Lake basin, and a segment of the Madison Range fault was reactivated (fig. 1).

FAULTS NORTHEAST OF HEBGEN LAKE

The long spectacular new scarps northeast of Hebgen Lake displace unconsolidated or weakly coherent material, chiefly colluvium. Commonly they are a short distance downslope from the contact of this surficial cover with bedrock. The local dip of each scarp is related to the kind of surficial material cut. Scarps in soil are vertical, whereas those in colluvium commonly are less steep, dipping 60° to 85° SW. The motion, as indicated by markings on the scarps, was chiefly down dip.

The surficial scarps are much steeper than the probable attitudes of the bedrock faults beneath: the faults are refracted to steep courses in the incoherent materials. As a result, the surficial material of the downdropped blocks pulled away from the scarps, leaving large open fissures (fig. 3). Locally the surficial materials sagged, closing the fissure; elsewhere the detritus collapsed along subsidiary fractures to form grabens and slump scarps. These effects make the exposed scarps higher than the actual vertical displacements on the bedrock faults that produced them.

FIG. 3. Gap of a simple fault scarp as exposed along the trace of Hebgen fault near Kirkwood Canyon.

The pre-existing Red Canyon and Hebgen faults are major structures; the Kirkwood and West Fork faults are small and inconspicuous both structurally and topographically. The position of the new Hebgen and Red Canyon scarps at the base of high bedrock ridges that stand above long talus slopes is presumptive evidence that these ridges are in part due to previous offsets along the same faults. There is also much evidence in the surficial materials of the West Yellowstone basin of episodic faulting during Quaternary time.

Only a few exposures were found of bedrock clearly cut and offset. In most places where a fault scarp abuts bedrock, the bedrock has parted along the fault trend, but irregularly along pre-existing joint surfaces or bedding planes; the general impression is that the rocks have simply fallen apart. At such places, it appears that the faults are being extended into previously unbroken rock.

In general, where the colluvial cover is thin and the bedrock is fairly well exposed, the scarp nearly coincides with the bedrock fault. Where the surficial cover is thick and the bedrock concealed, the position of the new scarp in relation to the projected trace of the bedrock fault seems to be a function of both the angle of slope and the thickness of the cover. A scarp that crosses thick but gently sloping surficial deposits maintains its established trend, but where the slope is steep the scarp may be deflected around the sinuous contact of colluvium and bedrock. In the latter case, the colluvial debris is both thick enough and inclined steeply enough to act as a coherent unit, and its contact with the underlying bedrock is a plane of gliding along which the surficial mass shifted downslope to take up the displacement on the concealed bedrock fault.

Red Canyon fault scarp.—The south-facing Red Canyon fault scarp (fig. 1) is about 14 miles long and as high as 19 feet near its midpoint. Near its southeastern end it is a series of small, gaping, discontinuous fractures. To the northwest, these fractures pass into small local scarps about 2 feet high along a low embankment formed during older movements. Both old and superimposed new structures increase in height toward U.S. Highways 287 and 191, which is offset by two parallel scarps. The northeastern scarp continues to the northwest, increasing in height gradually until it is about 14 feet high near Blarneystone Ranch, where at least two older episodes of faulting may be shown by higher, eroded scarps. The new scarp (fig. 4), superimposed upon one of the older ones, passes beneath the domestic quarters and storage sheds of the ranch, which were severely damaged by the earthquake.

Directly west of the ranch house the scarp gives way to small fissures, which end against a cliff of volcanic rocks. Surficial deposits above the volcanic rocks are broken by fissures of minor displacement that continue the trend, locally appearing as opposed scarps that define shallow grabens. A zone of these fractures about 1,000 feet wide extends to the mouth of Red Canyon, where it dwindles to a width of about 50 feet and consists of three to four low scarps.

Along the east wall of Red Canyon near its mouth, the fissure zone gives way to a single scarp, 6 feet high and dipping 55° SW. Northwestward, this scarp increases in height to about 10 feet, and locally 19 feet, and extends unbroken across Red Canyon Creek and along the south flank of Kirkwood Ridge (fig. 2). The scarp there curves to the southwest and decreases in height.

High, arcuate Kirkwood Ridge is formed of overturned Paleozoic rocks that dip moderately to steeply south or west toward the West Yellowstone basin. The Red Canyon fault swings through 115 degrees of arc along the curving ridge to remain approximately concordant to these Paleozoic rocks of the footwall: displacement has been down the dip of the beds. The hanging wall near the fault is largely buried by long talus slopes, but its rocks appear to dip gently toward the fault. The face of the high bedrock ridge above the fault is presumably itself an eroded fault scarp. The fault has been recurrently active during late Cenozoic time, and the upright limb of an anticline has been dropped along the overturned limb by the fault. At both ends of the arcuate ridge, the overturned Paleozoic beds roll to north-dipping, upright attitudes. The new fault scarp is high where the Paleozoic beds dip steeply basinward, but disintegrates into irregular zones of small scarps and fissures where the beds roll over. The ridge loses its commanding height also where the attitude of the rocks changes. Laramide structure has guided later normal faulting near the surface.

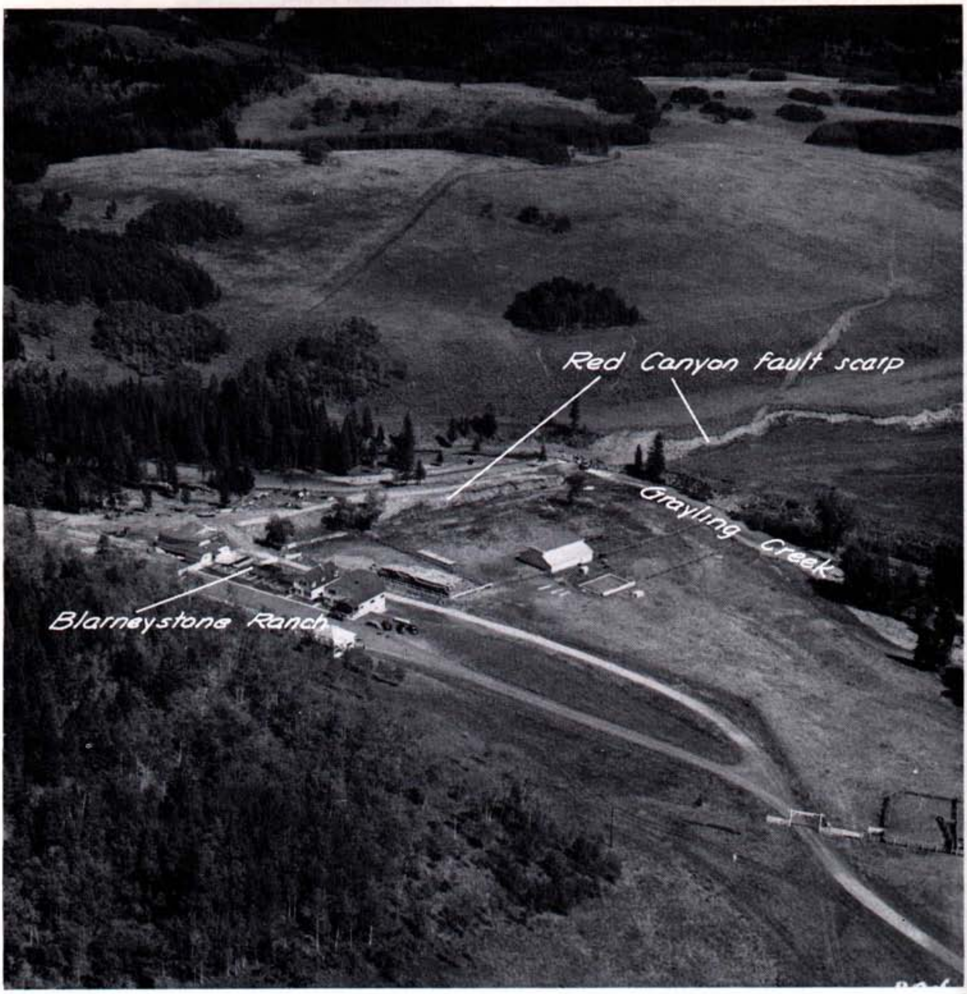

FIG. 4. Aerial view looking northeast at Red Canyon fault scarp where it crosses the Blarneystone Ranch. The new scarp, about 14 feet high, passes beneath domestic quarters of the ranch.

Kirkwood fault scarp.—Near the northwestern end of Kirkwood Ridge, where the Red Canyon fault joins the Kirkwood normal fault, a new south-facing scarp only about 2 feet high splinters off the Red Canyon fault scarp and extends eastward for about 1,000 feet. This new scarp coincides with the western end of the established Kirkwood fault.

West Fork fault scarp.—Parallel to and about 1 mile northwest of the western part of the Red Canyon scarp, a new scarp follows the West Fork fault for about 2 miles, trending N 65° E and facing valleyward. Near its western end it is about 4 feet high. Northeastward, it decreases in height and passes into a series of short fissures.

Hebgen fault scarp.—The Hebgen fault scarp, parallel to the northeast shore of Hebgen Lake, is a well-defined scarp about 6 miles long that trends southeastward into a zone about 100 feet wide and 1½ miles long of small fissures near and parallel to the contact between colluvium and bedrock. Height of the scarp is about 10 feet for most of its length, and in a few places is as much as 20 feet.

In at least two places the scarp is deflected upslope and around thick deposits of colluvium on steep slopes. The bedrock fault probably continues as a straighter feature beneath these deposits. Where the fault crosses a thick but gently sloping alluvial cone at the mouth of Kirkwood Creek, the fault is not deflected but persists as low valley-facing scarps.

The Hebgen fault is subparallel in strike to the Paleozoic strata. In some areas the continuous high scarp is coincident with strata having a steep southwest dip, favorable for slippage, and where the strata roll abruptly to an unfavorable attitude, the scarp disintegrates into small discontinuous scarplets and fissures. In other areas, as on the bedrock slopes north of Hilgard Lodge, the scarp is high but Precambrian crystalline rocks form the footwall. On Boat Mountain, a 9-foot high scarp entirely in colluvium is oblique to the strike of the Paleozoic rocks.

Deformation in West Yellowstone Basin

Subsidence.—The fault scarps formed northeast of the lake during the earthquake bound the area of wholesale subsidence of the West Yellowstone basin. By relating the post-earthquake level of Hebgen Dam to the bench-mark survey, and measuring the relative emergence and submergence of the pre-earthquake shoreline at 160 points about the post-earthquake lake, the measure of absolute subsidence was carried all around the lake. The entire lake basin subsided, the amounts varied from about 5 feet in Madison Arm and 13 feet in Grayling Arm to 22 feet in the main part of the lake, but only 10 feet at Hebgen Dam. Thus the lake basin was permanently warped during the earthquake, the northeast shore being submerged 5 to 10 feet, Grayling Arm submerged a few feet, and Madison Arm exposed about 5 to 10 feet, relative to the dam and the post-earthquake water level.

A seiche developed on Hebgen Lake as a result of this abrupt tilting. The few accounts by witnesses, the stream gaging records downstream from Hebgen Dam, and evidence seen later around the shore prove that the lake was thrown into violent motion, alternately draining some parts of the shore and flooding and sending large waves over others. Four large, early waves rose over Hebgen Dam. The lake continued to oscillate, with decreasing intensity, for about 11½ hours after the earthquake.

Changes in the lake bottom.—A detailed survey of the bottom of Hebgen Lake from the dam to the shallow parts of Grayling and Madison Arms was made with a continuous-profile acoustic sounder in September 1959. The known warping of the northwest part of the lake was shown also by the depth-sounding, which detected a reversal in gradient of the pre-lake Madison River channel near the dam; the lowest part of the channel subsided about 10 feet more than did the dam. Tilting was also shown in Grayling Arm. The soundings gave no indication of major faulting of the lake bottom. All the profiles have irregularities that might suggest faulting if taken individually, but these lack the continuity, between the closely spaced traverses, that would be expected along major faults.

Landslides carried at least 16 feet of debris into a deep part of the lake near Hebgen Dam. Three large slides and several smaller ones altered the lake depths in other places.

Deformation of the sand plain.—The surface of most of the West Yellowstone basin south of Hebgen Lake is a broad plain, sloping gently northwestward and underlain by obsidian sand and fine gravel several hundred feet thick. Major streams heading in the mountains cross the plain, but it is so permeable that no streams rise on its surface. Near the widely spaced streams the plain has been cut into steplike erosional terraces, but over most of its extent it is a monotonous surface, virtually uneroded since its deposition after early Wisconsin (late Pleistocene) glaciation.

The sand plain was deformed before 1959 by a number of small faults and monoclines with structural relief of as much as 15 feet each. Nearby early Wisconsin moraines were offset as much as 60 feet. Monoclines predominate at the surface, but they are believed to result from extreme near-surface refraction of faults that are normal at greater depth, or from draping over normal faults which do not break the surface. Almost all the structures were reactivated, with minor faulting and tilting of the surficial deposits during the 1959 earthquake (fig. 5), and the entire plain was tilted gently northward. The new tilt steepens gradually from West Yellowstone northward; most of the reactivated structures are in the least tilted part.

The pre-earthquake monoclines appear as gentle north-facing rises, 1 to 15 feet high, that interrupt the smooth northward slope of the sand plain. Frontal slopes of the rises commonly range between 5 and 10 degrees; slopes of 20 degrees are uncommon. The rises are readily distinguished by their relative straightness, and generally by their gentler slopes, from the irregularly curving sides of stream terraces. In front of some rises are broad, very shallow sags, 100 feet or more wide and commonly about a foot deep. Most of the rises lie in a west-trending arcuate zone, gently convex to the north and 6 miles long, that extends from the Madison River to the west edge of the sand plain. The individual structures are separable into two groups, trending about N 70° W and N 75° E.

All of these structures were reactivated during the earthquake. The new local relief on individual structures ranges from a few inches to nearly 3 feet, and is represented chiefly by faulting in some places, by warping in others, and by a combination of both elsewhere (fig. 5). The most obvious new features are scarps that face north and are vertical, or even dip steeply southward beneath the upthrown blocks. The down-dropped block in places is driven tightly in under the relatively upthrown block so that the latter overhangs slightly.

Monoclinal warping during the earthquake is made obvious where dips are more than several degrees by correspondingly tilted lodgepole pine trees. The base of each monocline is commonly broken by a nearly continuous miniature "mole-track" thrust fault which dips gently toward the larger structure at the surface but steepens downward. Such a fault is marked by the hammer in figure 5.

Scarps and fissures were formed during the earthquake throughout the length of the pre-existing monoclines. Scarps higher than a foot are continuous along the upper parts of the old rises, whereas fissures and lower scarps are discontinuous and overlap in echelon along the monoclinal slopes. Vertical offsets are almost invariably down toward the topographic basin, and the highest scarps tend to be on the highest monoclines. The echelon fissures and scarplets show no preferential strike-slip displacement of opposite walls, so their arrangement is not due to strike-slip offset. They are thought to have been produced as earthquake waves passed through the

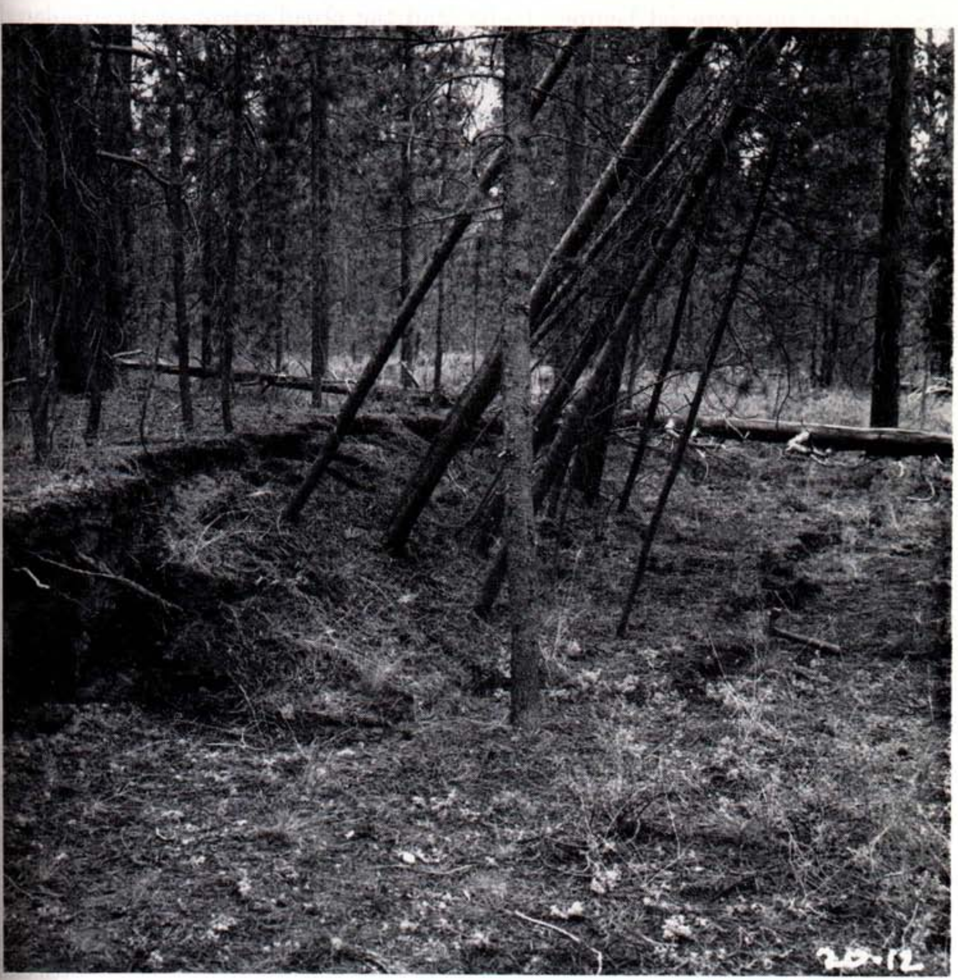

FIG. 5. New scarp and monocline in the sand plain. Fault, left, with tightly closed fissure, gives way to steep monocline, center, which gives way in turn to a gentle monocline.

surface layers of the unconsolidated obsidian sand where it was then being folded along the monoclines.

Numerous features show that these structures have grown during repeated deformation. There is a nearly universal coincidence of new and old scarps. The continuity of the structures, both new and old, their occurrence in linear zones that in places trend into exposed bedrock faults, and the broad extent of the displaced levels of the plain show the structures to be due to bedrock offsets. The structures cannot be due to basinward slumping of the surficial deposits, for on the very gentle slope of the sand plain any such slumping would have produced horizontal separations. Features such as the anomalous dips of fault scarps and the mole-track thrusts are attributed to the combined effects of extreme surficial refraction of bedrock normal faults, which characteristically change dip upward into weak, unconsolidated material, and contemporaneous mutual slump of both walls of the refracted faults.

The occurrence of major earthquakes—some of them probably much more severe than the 1959 one—in Wisconsin and Recent time is shown by the numerous fault scarps that cut moraines and other surficial deposits around the West Yellowstone basin. Where surficial deposits of varied Wisconsin and Recent ages are cut by continuous structures, the structural relief increases with age of deposit, showing repeated past movements.

DEFORMATION IN MADISON VALLEY

The spectacular effects of the earthquake are near Hebgen Lake, in the West Yellowstone basin and adjacent parts of the Madison Range, but deformation extended many miles to the west. Part of the Madison Valley near the latitude of Hebgen Lake also subsided, though probably not as much as the lake basin. Releveling of bench marks after the earthquake demonstrated that the Madison Valley subsided 7 feet near the mouth of the Madison River Canyon. The line of levels trends obliquely into the topographic trough of the valley, then follows the trough northward. Five miles below the mouth of the canyon, the subsidence was little more than a foot, and at Kirby Ranch, $3\frac{1}{2}$ miles farther, it was only a few inches. No subsidence was recorded by bench marks farther north along the line. The greatest subsidence shown is at the southernmost bench mark.

Other data, relative rather than absolute, indicate a complex pattern of subsidence for Madison Valley. Ditches carrying water around an alluvial fan at Sheep Creek were tilted, and some became useless as a result. Farther west, the north end of Cliff Lake (fig. 1) subsided $1\frac{1}{2}$ to 2 feet relative to the rest of the lake, as evidenced by shoreline changes. The water level of Wade Lake, north of Cliff Lake, was reportedly higher after the earthquake, but without obvious difference in relative level from one end to the other.

The Recent fault scarp along the west flank of the Madison Range was reactivated for a length of several miles south of Sheep Creek (fig. 1), and a discontinuous new scarp as high as 3 feet was formed. At the mouth of a canyon where the old scarp was in extremely coarse morainal debris, no new scarp formed, but jostling of the boulders heightened the old scarp by several feet, as demonstrated by the stretching of a wire fence.

DEFORMATION IN MADISON RIVER CANYON

By comparing the pre-earthquake Bureau of Public Roads highway profile in Madison River Canyon with the post-quake highway profile as defined by the individual rod readings of the Coast and Geodetic Survey releveling, the measure of absolute subsidence was carried into the canyon to Earthquake Lake at the upper end and nearly to Madison Slide at the lower end. At the mouth of the canyon, where there is no evidence for reactivation of the Madison Range fault nor for warping across it, the highway subsided from 7 to 8 feet on both sides of the fault, and remained at this level to the point where the level line left the highway, 2,000 feet into the range from the fault trace. (The maximum subsidence in the West Yellowstone basin was determined also by highway profile comparison. A segment of the highway about a half a mile in length, centered a mile southeast of Hebgen Dam, was 22 feet below its former position. There are no bench marks in this interval; maximum bench mark subsidence was about 19 feet, at a point three miles farther southeast.)

Near Beaver Creek, in the upper end of the Madison River Canyon, the highway enters a basin filled by till and alluvium. The bench mark on the bridge at Beaver Creek subsided about 8 feet, and beyond this point the subsidence of the highway increased smoothly to 14 feet where the road disappears beneath Earthquake Lake, 4,000 feet southwest of Beaver Creek.

Further releveling was done by the Bureau of Public Roads during 1960 (Lynn D. Tingey, written and oral communications). Along 300 feet of the highway, 2,900 feet southwest of Beaver Creek, there was as much as 9 feet of new subsidence between September, 1959, and the spring of 1960, which brought the total subsidence to a maximum of 20 feet; this interval coincides with a topographic trough in glacial till which Myers and Hamilton believe to be a collapse feature above a reopened bedrock fault, and which Witkind and Fraser consider to be due to surficial slump and compaction. Along part of the steep colluvial shore of Earthquake Lake, there was 1.0 to 1.8 feet of new subsidence between the spring and fall of 1960, presumably due to slumping toward the lake; subsidence during the earthquake was indeterminable here, as the highway was buried by the lake.

INTERPRETING THE DEFORMATION PATTERN

Changes in altitude during the earthquake were almost entirely downward: the earthquake resulted from the sudden collapse of a broad area. The high general altitude of the mountains, however, is evidence for regional, epeiric uplift. Broad, gradual, regional uplift is indicated, probably generally unaccompained by earthquakes; this uplift has been interrupted intermittently by sudden, earthquake-producing dropping of basin blocks.

There is disagreement within our group regarding the interpretation of the data on a smaller scale. The northeastern limit of significant subsidence and warping during the 1959 earthquake is the Red Canyon and related fault scarps, the southeastern limit is a little north of West Yellowstone, and the northwest limit is in Madison Valley; but the southwestern limit is uncertain, as is the behavior of the crest of the Madison Range. Subsidence of Hebgen Lake, of the area between the

Red Canyon and Hebgen faults, and of Madison Valley is conclusively demonstrated by a combination of geodetic, engineering, and geologic evidence. Contrasted interpretations are proposed regarding the significance of the data in Madison River Canyon and regarding the role of the Madison Range in the deformation.

Myers and Hamilton picture a compound basin of new subsidence plunging gently eastward across the southern part of the Madison Valley and the Madison Range to Hebgen Lake, so that part of the range has subsided along with the bordering areas although to a lesser extent (fig. 6). This interpretation can be referred to as the "single-basin concept". The subsidence basin slopes gently on its southern flank, but its northern side ends obliquely and abruptly against the high scarps northeast of Hebgen Lake. Among the indications of subsidence of the Madison Range are the engineering data in Madison River Canyon, which show continuous subsidence of the highway where it could be resurveyed—that is, where it was not covered by the Madison Slide and Earthquake Lake—and the trend of well-controlled isobases of new subsidence into the Madison Range at high angles from Hebgen Lake. Thirteen of the points by which subsidence was determined about the shore of Hebgen Lake are on bedrock, and one of these dropped 19 feet; one bench mark is also on bedrock. These bedrock points subsided compatibly with points on surficial materials, and this, considered with the smoothness of subsidence demonstrated in practically all places save those obviously broken by landslides or slumps, is taken

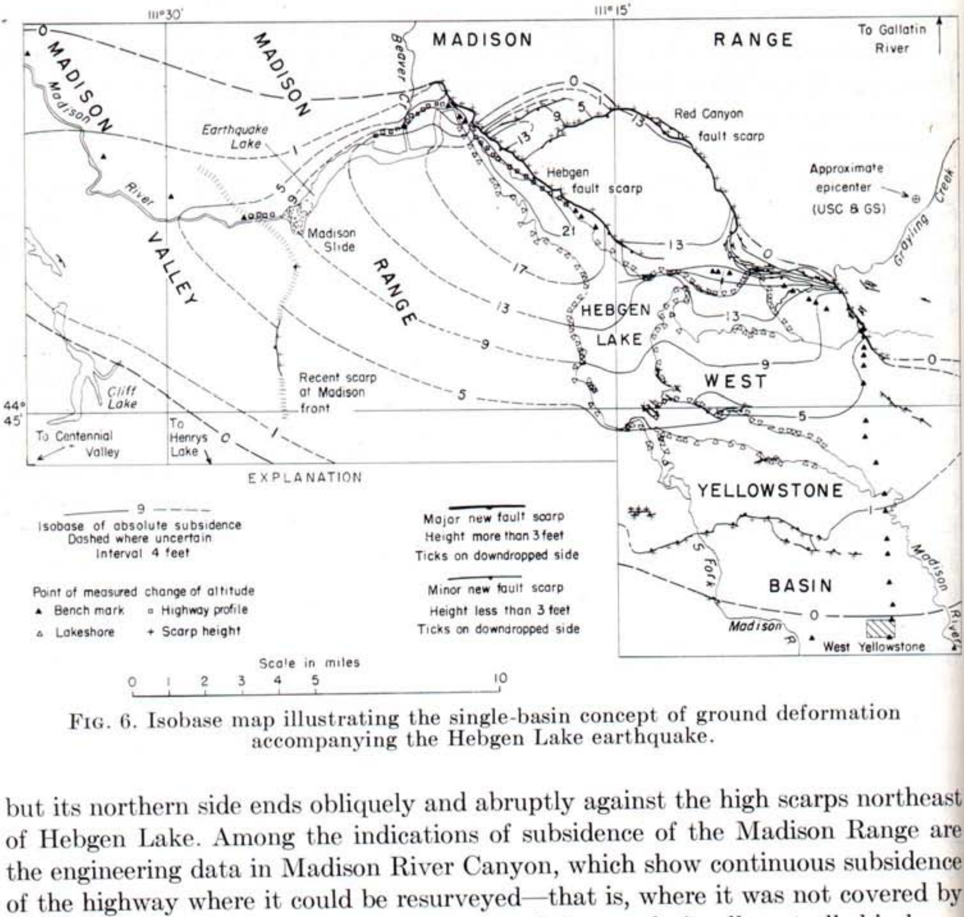

FIG. 6. Isobase map illustrating the single-basin concept of ground deformation accompanying the Hebgen Lake earthquake.

to indicate that virtually all of the subsidence was tectonic. The known subsided areas, from Cliff Lake to the Red Canyon fault, fall in a broad east-trending zone. It is held that the major fault scarps northeast of Hebgen Lake are bedding-plane faults controlled by the attitudes of strata in Laramide structures which cannot extend very deep, and therefore that these faults are but the near-surface expressions of deeper warps or faults which may have quite different trends. A first-motion study of the earthquake by Ryall (1961) suggested offset on a deep fault striking about N 80° W, rather than on a structure striking north-northwest as do the major surface breaks. As the southern part of Madison Valley has been much deformed by east-trending structures during late Quaternary time, and as similar new trends are apparent in structures continuing eastward as far as Gibbon River in Yellowstone Park, the interpretation is made that the Madison Range family of north-northwesterly structures is now being deformed obliquely by east-trending structures related to those controlling Centennial Range and Centennial Valley. The earthquake is believed to have resulted from the sudden collapse of a broad basin, bounded obliquely by faults on the northeast.

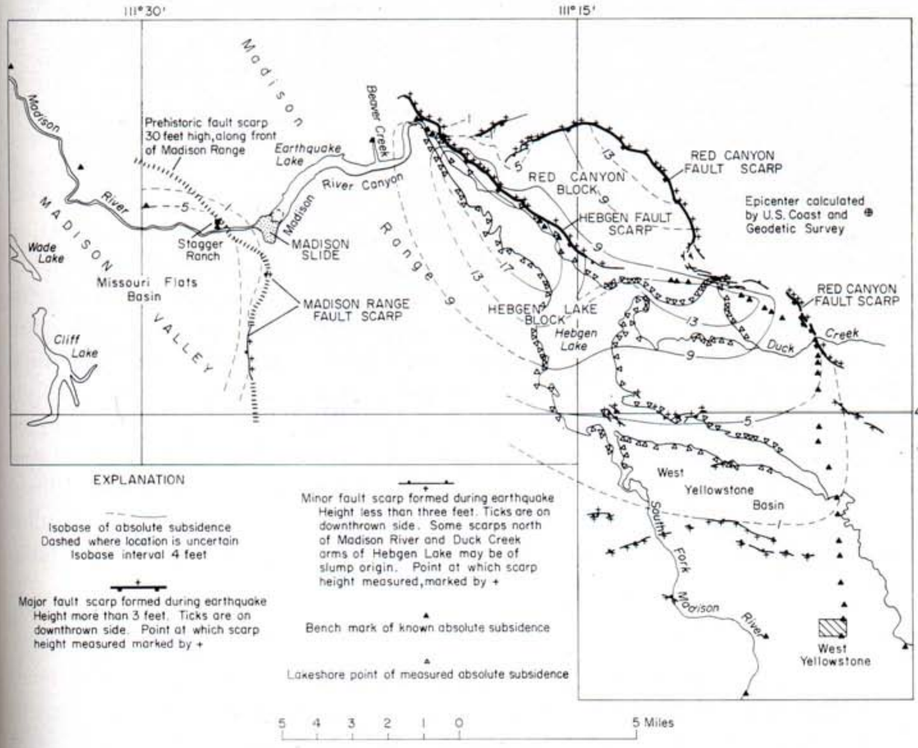

FIG. 7. Isobase map illustrating the fault-controlled dual-basin concept of deformation.

Witkind and Fraser make the interpretation, which can be termed the "dual-basin concept" (fig. 7), that the deformation was largely restricted to two fault-controlled basins on either side of the Madison Range, and that the crest of the range changed relatively little in altitude. Implicit in this view is the fundamental importance of the reactivated faults. It is held that movement on one or more of these caused the earthquake, and that the type and amount of movement determined the configuration of the warped basins. Accordingly, either or both the Red Canyon and Hebgen faults may be the causative faults of the earthquake; possibly one is a splinter off the other. They appear to be genetically related to the deep-seated fault mentioned by Ryall (1961, p. 63). In this interpretation the pattern of deformation shown on the isobase maps is considered to be inexact: compaction and slump are superimposed on the true bedrock subsidence. Virtually all the bench marks, the highway, and most of the lake shore are on surficial deposits. Any deformation map, then, shows the pattern of the deformed surface which is not necessarily the pattern of the deformed bedrock. Repeated leveling by the Bureau of Public Roads in Madison River Canyon shows a spot total of 20 feet of subsidence, much of it post-earthquake, local, and erratic. This and the locally numerous sand spouts formed at the time of the earthquake suggest that not all the subsidence here is tectonic. Some may be due to compaction and slump of the surficial deposits on which the road is built.

Witkind and Fraser believe that faults are the main controls for deformation associated with earthquakes, that warping derives from faulting, and that the main warp axis parallels the principal fault zone (Hebgen-Red Canyon in this earthquake). It is held that secondary transverse warps are superimposed on the main warp as a geometric consequence of uneven sag along the principal fault zone which diminishes to zero at its ends. In this view, warping does not define new basins, but is a minor consequence of movement on old faults. Thus, any tectonic subsidence in the Madison Range results from movements along the faults. This fault movement, together with parallel warps, actually increased the relief of the Madison Range and accentuated the old basin on each side. As Centennial Valley is 25 miles from the epicenter, it is believed to have no special bearing on the Hebgen Lake earthquake.

LANDSLIDES AND RELATED PHENOMENA

The 1959 deformation of the Hebgen Lake area was accompanied by surficial gravity sliding, ranging in importance from minor slumps of hillside colluvium to the great Madison Slide formed by the catastrophic failure of a lofty bedrock ridge. Slides were most abundant in an area about 20 miles north-south and 50 miles east-west around the earthquake epicenter. Many rock falls and debris avalanches from cliffs were set in motion by the main earthquake and by after-shocks. Massive slumps of colluvial mantle, jolted downhill by earthquake shocks, were commonly marked by fissuring along ridge crests and, rarely, by compressional folds and underthrust faults in surficial deposits at the bases of the slopes. Most of the damage to Hebgen Dam was caused by massive slumping from the east side of the valley. Debris slides into Hebgen Lake were probably facilitated by the saturated character of the colluvium along the lake shore.

All the fatalities resulted directly from landslides, as did most of the damage to roads and highways. The latter represented a dollar loss at least comparable to that sustained by buildings and other structures.

Evidence of churned ground indicates that in small areas, generally on strong bedrock units with little soil cover, surficial material and bedrock blocks were thrown upward.

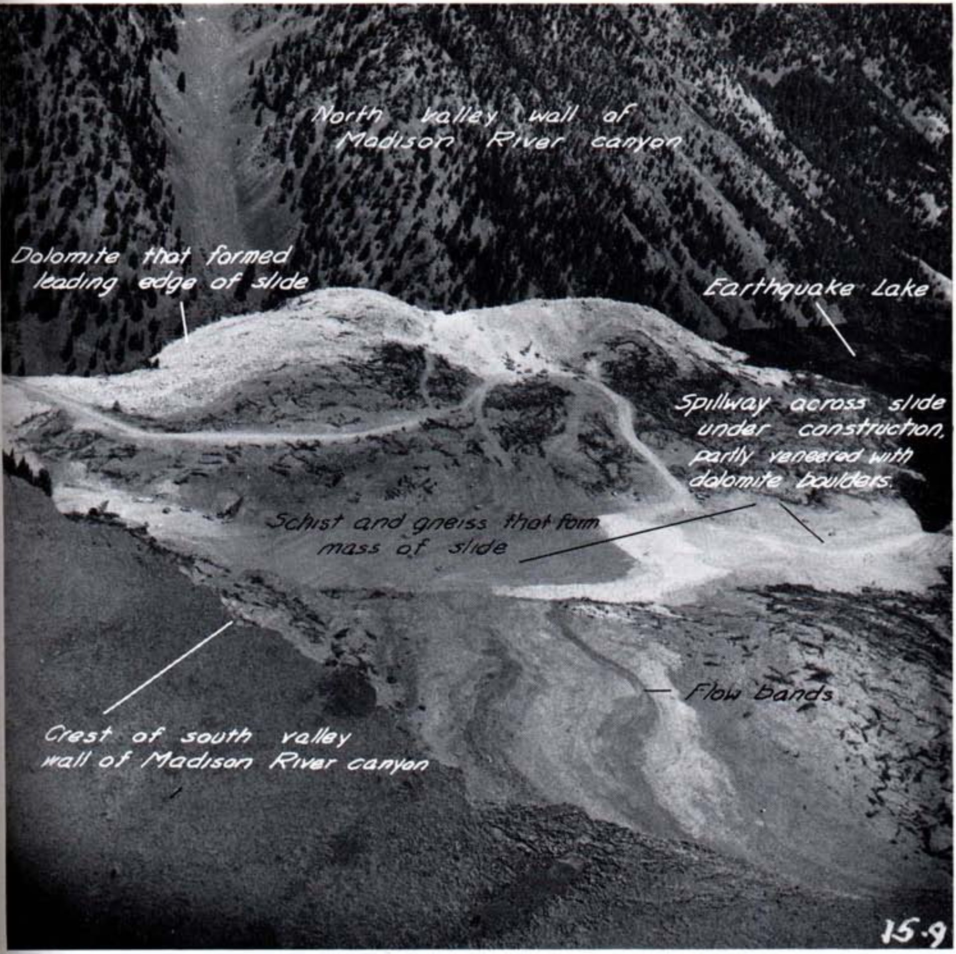

FIG. 8. Oblique aerial view looking N. 15° W. at the Madison Slide. Nearly a mile of the north wall of the Madison River Canyon is shown, as measured at the lowest exposed level.

MADISON SLIDE

A disastrous landslide was triggered by the earthquake in the canyon of the Madison River, 6 miles downstream from Hebgen Dam (fig. 8). Thirty-seven million cubic yards of broken rock slid into the canyon, burying a mile of the river and highway to depths as great as 220 feet. At least 26 people in a campground were buried by the slide, and many more people camping near the edge of the slide were injured. (Two other campers were killed by a rolling boulder at Cliff Lake, west of Madison Valley.) Water ponded by the slide formed Earthquake Lake, which within 3 weeks was full, nearly 200 feet deep and extending almost to Hebgen Dam (fig. 1).

Local structural and geomorphic conditions had here produced a dynamically unstable slope, ready to be set in motion by an earthquake or violent flood. The canyon is narrow and steep walled. The south wall, where the slide occurred, is 1,000 to 1,500 feet high, and is cut into sheared schist and gneiss whose dominant structures dip down the slope, although at angles steeper than the slope. The rocks were deeply weathered, and the lower slopes were mantled by talus. The western part of the slope that slid was the steepest, and was buttressed at its base by a wedge of strong dolomite, acting as a large retaining wall, dipping more steeply than the nearly 45 degree slope and cropping out in craggy spurs. The eastern and upper parts, underlain by schist and gneiss, had slopes averaging only 27 degrees.

Within moments after the main earthquake shock, a section of this south wall 2,200 feet long and 1,300 feet high slid northward into the canyon and well up the other side, spreading over an area of 130 acres. The slide broke obliquely through the dolomite buttress; the dolomite was broken 350 feet above the valley floor at the west end, but the break descended eastward in the weaker rocks probably to near river level. The scar at the top of the slide in places cut 300 feet beyond the ridge crest, or 200 feet vertically down the back slope.

The west part of the slide moved faster than the east part; a velocity on the order of 100 miles per hour was probably attained as the mass moved 1,600 feet along a 30 degree slope, and a violent air blast was sent out in front of the slide. Most of the west part of the slide crossed Madison River and rode up the north valley wall, and the momentum carried its surface as high as 430 feet vertically above the river. The east part moved more slowly, and much less of it crossed the river; pressure ridges and closed depressions formed on its surface.

The shattered dolomite torn from the buttress of the west part of the slope rode forward on the front of the slide. The top few feet of the slide was composed of large blocks of rock, but beneath this, clay, silt, sand, and blocks of all sizes were jumbled together. The fine component was mostly decomposed material from colluvium and weathered bedrock, but presumably grinding during movement added more.

Something like 28 million cubic yards of rock were removed from the mountainside. During movement, this increased in volume to acquire a porosity of about 25 percent; volume of the material deposited at the bottom was about 37 million cubic yards. This is about the same as the volume of the Turtle Mountain slide at Frank, Alberta, in 1903, and about one-fourth smaller than the Gros Ventre slide in northwestern Wyoming in 1925.

If faults or other through-going structural elements controlled the surface of rupture of the Madison Slide, they are not evident. Rather, it seems to have been determined by the structural orientation and the depth of weathering and fracturing of the bedrock, and by the ability of the dolomite buttress to withstand the thrust of the slide mass.

Kirkwood Earthflow

A long-inactive, large earthflow in the North Fork of Kirkwood Creek was reactivated by the earthquake. Half a mile long and 400 to 800 feet wide, the earthflow moved at least 100 feet in the month following the earthquake, and was still moving by continuous slow flow when studied on September 18, 1959.

The flow heads in an area of old and new slide scars developed in the soft, clayey Morrison Formation just south of the divide between Kirkwood and Cabin Creek (fig. 1), and terminates in a steep rounded front marked by abundant crevasses in its upper part and by pressure ridges and small underthrusts lower down. The overall gradient from the top of the scarps to the toe is about 10 degrees, but in the middle two-thirds the gradient is little more than 6 degrees. The surface of the flow is in part heavily forested, and hundreds of tilted and fallen trees reflect the recent movement (fig. 9); sag ponds on the flow were tilted, broken, and drained.

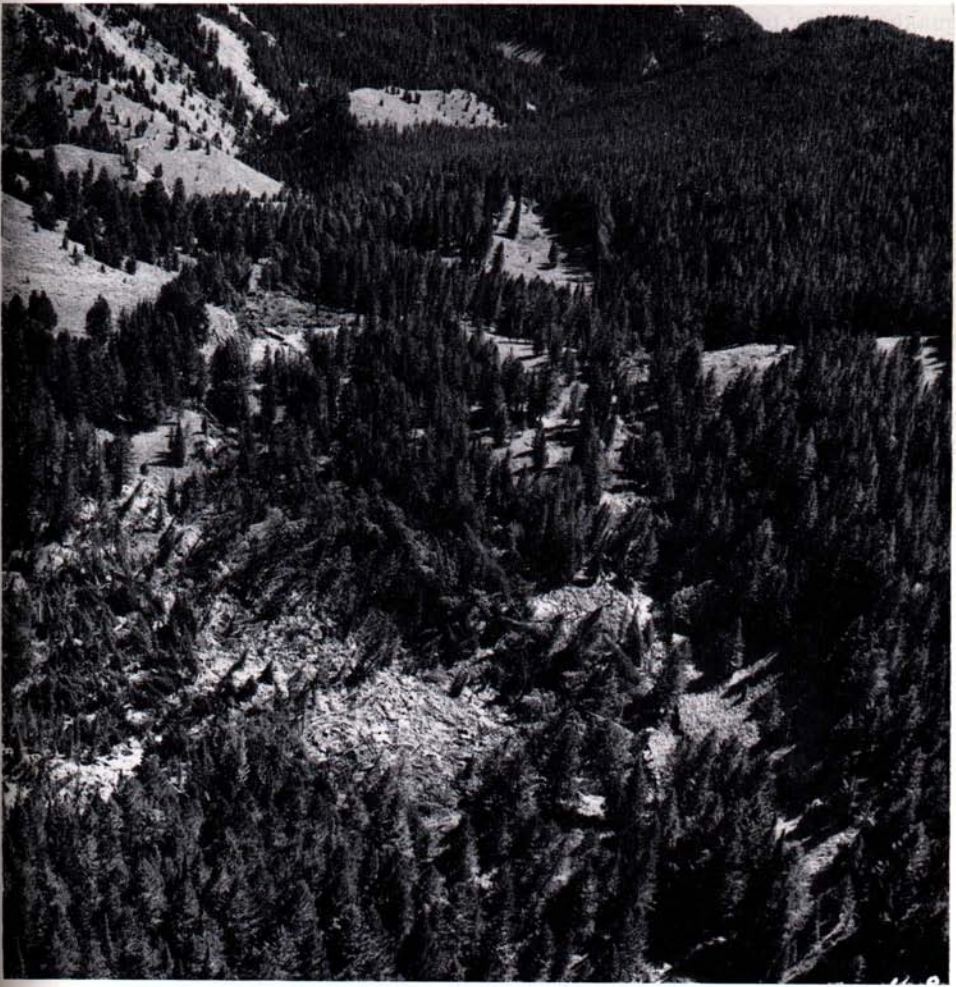

FIG. 9. Aerial view of the Kirkwood earthflow, Sept. 3, 1959, looking south in the direction of movement. The area of jumbled blocks and tilted trees in the foreground is near the head of the flow.

The scarp at the head of the flow was the area of greatest new downward and forward movement. The toe of the flow was raised and thickened, forming abundant new pressure ridges and underthrusts, but did not much override the ground in front.

Although no new movement was recognized on 1:10,000 scale air photographs taken 5 days after the earthquake, motion must have been caused indirectly by the earthquake. An increase in the flow of ground water was noted after the earthquake in many parts of the Hebgen Lake area, and perhaps ground water from the bedrock soaked into the flow and lubricated it. The previous gradient of the flow was increased 35 feet per mile by local warping due to the earthquake, and the lower half of the flow was dropped 3 feet along a fault crossing it.

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