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Reconnaissance Study of Quaternary Faults in and South of Yellowstone National Park, Wyoming

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Abstract: Normal faults offset a bedrock surface scoured by Pleistocene ice in several areas within and south of Yellowstone National Park. Recurrent earthquake shocks and fresh appearance of some scarps suggest that movement is continuing along some faults. Four systems of faults are described.

Quaternary movement occurred along more than 60 faults on the Mirror Plateau, 15 miles northeast of Yellowstone Lake. Faults trend northwest, and several are more than 6 miles long. Maximum displacement exceeds 250 feet. The majority have northeast blocks downdropped, but some grabens and horsts are present. Eocene to Pliocene igneous or pyroclastic rocks are displaced. Ice moved southwest and south from the Beartooth and Absaroka ranges, nearly at right angles to the fault trends. Drainage in many ice-scoured valleys was disrupted by faulting, and small lakes (such as Mirror Lake) formed on downthrown blocks. Thermal activity occurs along some of these faults.

Directly east of Mirror Plateau, the Lamar normal fault has a displacement of 1300 + feet; perhaps 1000 feet of this may have occurred during Quaternary time.

The Yellowstone Falls fault system cuts Pliocene rhyolite southeast of the Upper Falls of the Yellowstone River. Faults trend northwest; maximum displacement exceeds 200 feet.

The Solfatara fault system trends north-northwest, cuts Pliocene rhyolite, and has a maximum Quaternary displacement of about 200 feet. The Hering Lake fault system is a northern extension of the Teton fault, trends northward, and cuts Pliocene rhyolite and rhyolitic welded tuff. Maximum displacement is about 200 feet. West-flowing streams established on bedrock scoured by ice were disrupted, and Beula, Hering, and South Boundary lakes formed on the downthrown (east) blocks.

The sharp angular unstepped appearance of fault scarps 50 to 200 feet high in these fault systems suggests that each scarp of this type was formed by one continuous movement. The displacement along faults associated with the Hebgen earthquake of August 1959 is commonly less than 20 feet. The abundance of Quaternary faults and the record of 18 earthquakes in historic time suggest that additional faulting and earthquake activity can be expected in the future. Recognition of this probability should influence the location and type of construction of buildings and other facilities.

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INTRODUCTION

This paper summarizes data on four Quaternary fault systems and several separate faults in and south of Yellowstone National Park, Wyoming (Fig. 1). Most of these have not previously been described. They are located in densely wooded areas with rough terrane. During parts of 14 field seasons, reconnaissance was done by plane, helicopter, boat, horse, jeep, and on foot. Investigations were terminated before the Hebgen earthquake (Witkind, 1959; Matthews and Roberts, 1960) of August 17–18, 1959, in and west of Yellowstone National Park, and subsequently there was no opportunity to examine the fault areas for evidence of renewed movement.

As a result of the Hebgen earthquake, with its attendant loss of life, property damage, and conspicuous crustal movements, both scientific and popular attention has been drawn to studies of Quaternary faults. Those in and south of Yellowstone National Park provide data that help place the Hebgen earthquake and its associated phenomena in their proper geologic perspective.

ACKNOWLEDGMENTS

The writer is greatly indebted to John de la Montagne for assistance in this study and for providing a perpetual challenge to ruling theories. G. M. Richmond made available his unpublished maps of glacial debris in Jackson Hole and has given valuable counsel throughout the investigation. Mr. and Mrs. Eliot Davis of the National Park Service have facilitated the work during many field seasons, in both Grand Teton and Yellowstone national parks. W. B. Hall and J. M. Hill provided a plane and took many photographs of faults and associated glacial phenomena. The writer appreciates the opportunity arranged by Mr. Hall to review in the field the evidence for high-level glaciation in the Gallatin Range. J. M. Lawson, William Kennedy, and Arthur Gervais of the U. S. Geological Survey made available a helicopter for use in less accessible areas of Yellowstone National Park during the summer of 1958. E. B. Leopold made pollen determinations from samples of post-rhyolite lacustrine strata in the Yellowstone Falls area.

The studies were conducted and the report prepared with the cooperation of the Geological Survey of Wyoming, the Department of Geology, University of Wyoming, and the U. S. National Park Service.

PREVIOUS WORK

The literature dealing with Quaternary faults and modern earthquakes in and south of Yellowstone National Park is meager, whereas that on glaciation is much more extensive. Howard (1937) described post-rhyolite faulting in several areas of Yellowstone National Park but did not consider it to be postglacial. Pardee (1950, p. 369–379) discussed postglacial faulting in the Yellowstone Valley north of the Park boundary, and along the east side of the Madison Valley, 15 miles west of the Park. Several of the Quaternary fault systems within the Park have been briefly mentioned (Love, 1959, p. 1782).

In Jackson Hole, there are two major normal faults of late Cenozoic age, the Teton fault on the west side of the Hole and the Hoback fault on the southeast. Both show some post-glacial movement (Love and Montagne, 1956, p. 169–178). A northern extension of the Teton fault continues a short distance into Yellowstone National Park (Fig. 1). Blackwelder (1915, p. 214–215) considered the east face of the Teton Range to be a fault-line scarp formed not later than middle Tertiary time. Horberg (1938, p. 64) and Edmund (1951, p. 65) considered part of it to be Recent. Fryxell (1938) described postglacial faulting along the east flank of the Teton Range. Love and Montagne (1956) discussed evidence for post-glacial movement along these faults and for tilting of Jackson Hole during Recent time. Lavin and Bonini (1957) made a reconnaissance gravity investigation along the Teton fault.

Unpublished studies of late Cenozoic faults in the Madison Canyon area (Fig. 1, loc. A) and Mount Sheridan area (Fig. 1, loc. B) have been made by F. R. Boyd (1957, Ph.D. thesis, Harvard Univ.). C. W. Brown (1957, Ph.D. thesis, Princeton Univ.) made similar studies in the northern part of the Park (Fig. 1, loc. C).

SUMMARY OF GLACIATION

Some of the late Cenozoic normal faults south of Yellowstone National Park have displacements of 10,000 feet or more (Love, 1956b), and movements have continued to Recent time. Therefore, to distinguish Tertiary and Quaternary faults, it has been necessary to study the distribution of glacial ice. Figure 2 shows glaciated and unglaciated areas, directions of ice movement, and, in the southwestern part of Yellowstone National Park,

High-altitude vertical photo shows Lamar River (A), Mirror Plateau (B), Mirror Lake (C), Deep Creek (D), and Quaternary fault scarps that have dammed or offset drainage. Details of faults are shown on Figure 3. Width of photo is approximately 8 miles; north is at top. Photo by Army Map Service.

PART OF MIRROR PLATEAU FAULT SYSTEM

Figure 1. Graben north-northeast of Wapiti Lake. View looking south-southeast at ponded and deflected drainage. Rounded scarps are in Pliocene rhyolite and are about 350 feet high.

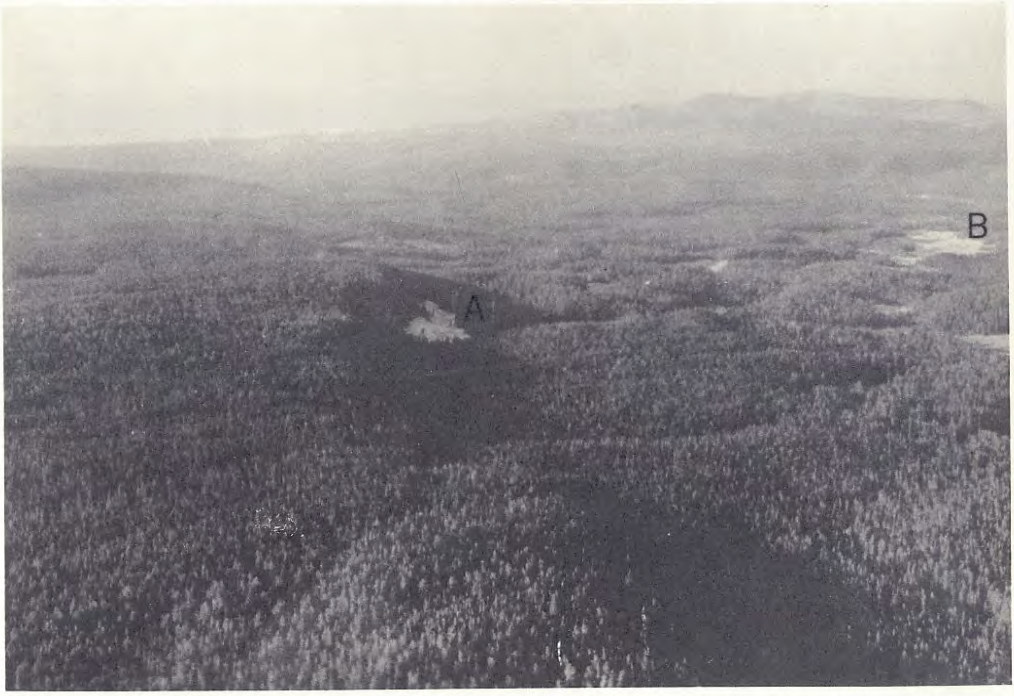

Figure 2. Hot springs emerging along fault scarp (A) and other large hot springs (B) in graben. View looking north along scarp 1 mile north-northwest of Wapiti Lake. Height of scarp is about 200 feet.

NORMAL FAULTS IN THE WESTERN PART OF THE MIRROR PLATEAU FAULT SYSTEM

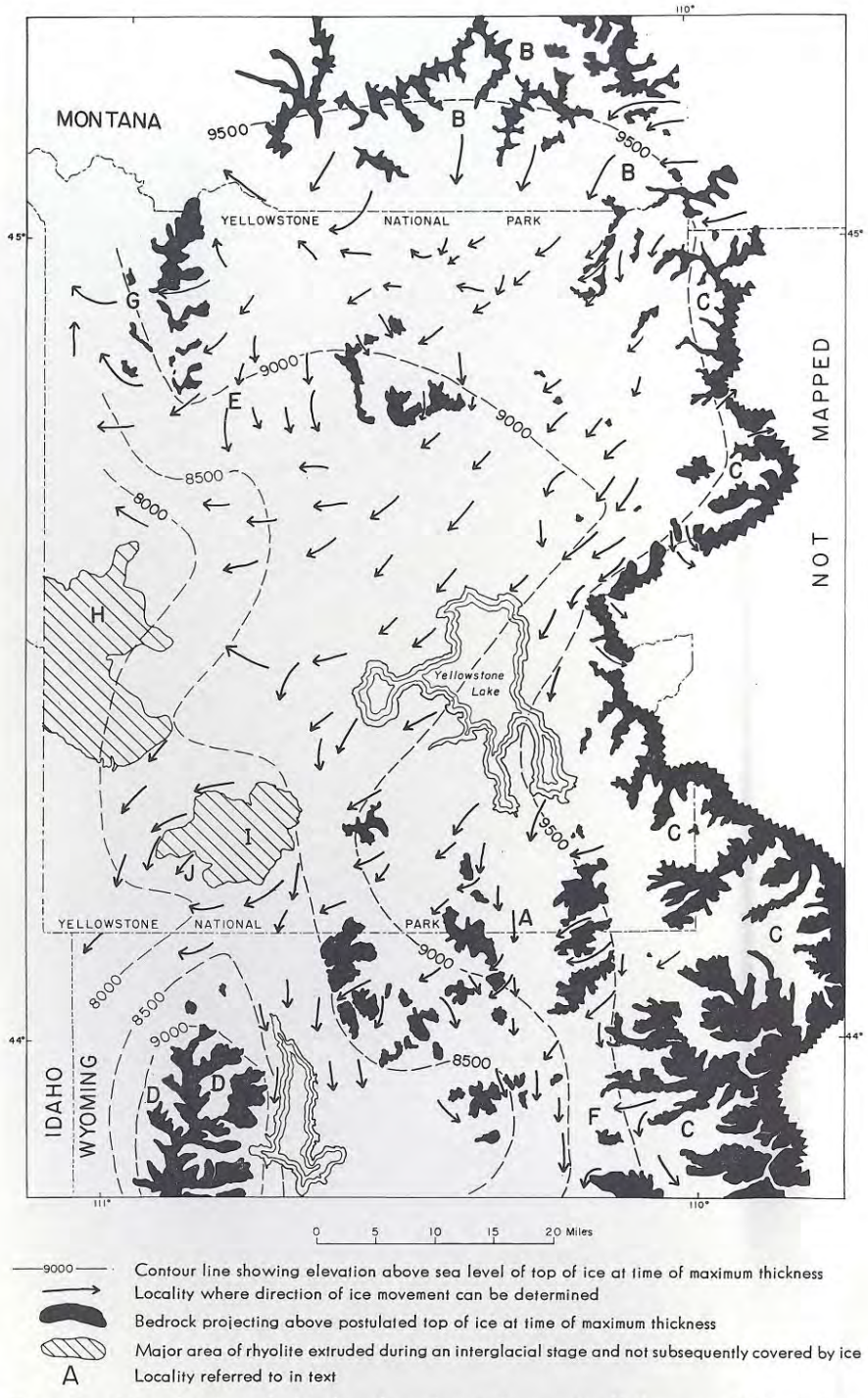

Figure 2. Map showing glaciated and unglaciated areas in Yellowstone Park region, direction of ice movement, and elevation above sea level of top of ice at time of maximum thickness

60–80), Edmund (1951, p. 67–78), Richmond (1948, p. 1400–1401), Love (1956b, p. 149–150), and Montagne and Love (1957, p. 1861) have described glaciation in Jackson Hole and adjacent areas.

Abundant large pink Precambrian granite erratics in and adjacent to south-trending glacial grooves and scour lines that cut bedrock of Cretaceous sedimentary rocks are found along the Yellowstone National Park boundary directly south of Yellowstone Lake (Fig. 2, loc. A). Three possible exposed source areas for these granite boulders are: the Teton Range, 25 miles to the southwest, Buffalo Fork Mountain, 18 miles southeast (Fig. 2, loc. F). and the Beartooth Mountains (Fig. 2, locs. B) 55 miles to the north. A fourth possible source area could be concealed under Yellowstone Lake, where Precambrian rocks might have been brought up along the northern part of the Buffalo Fork thrust fault (Fig. 1). Rocks as old as Ordovician are exposed along this fault (Love and others, 1955). A regional study of directions of ice movement (Fig. 2) indicates that the boulders probably came from the north, either from the Beartooth Mountains or from under Yellowstone Lake.

An analysis of the data indicates that within this area the major sources of ice accumulation were the Beartooth Mountains along the northern margin of Yellowstone National Park (Fig. 2, locs. B), the Absaroka Mountains along the eastern margin (Fig. 2, locs. C), and the Teton Range (Fig. 2, locs. D).

Ice during each stage cut a surface across hard and soft rocks ranging in age from Precambrian to Pleistocene. The final composite scoured surface has mountainous relief and in several areas, particularly those where Buffalo ice was thickest, is characterized by giant ice-cut grooves 1 to 5 miles long, 100 to 1000 feet wide, and 50 to several hundred feet deep. In many places in Jackson Hole slightly tilted Pleistocene lacustrine and fluviatile strata were overridden by ice.

QUATERNARY FAULTS

General Discussion

A basic assumption in determining the occurrence and magnitude of Quaternary faults is that any preglacial fault scarps trending at or nearly at right angles to direction of ice movement would have been obliterated or conspicuously modified by ice if they occurred below the upper limit of ice (Fig. 2). Therefore, in glaciated areas, unmodified scarps at right angles to direction of ice movement are considered to be fault scarps of Quaternary age.

Criteria used for recognition of Quaternary faults are: (1) linear offset of bedrock, (2) sharp, unmodified linear breaks in topography at or nearly at right angles to glacial scour lines, glacial grooves, or postglacial drainage; (3) lateral offsets of postglacial streams, (4) ponding, waterfalls, or rapids in postglacial streams; (5) distribution of hot springs coinciding with linear breaks in topography.

Almost all the Quaternary faults are in rhyolite or rhoylitic welded tuff, which characteristically supports dense stands of timber (Pl. 1), and which weathers so readily that exposures are poor. The faults were mapped on air photos and topographic maps. Field studies were made wherever circumstances permitted. Specific features of these faults are rather difficult to observe on the ground, however, because at most localities scarps appear as steep slopes covered with shattered rock and abundant trees (Pls. 2, 3, 4).

A generalized summary of Quaternary chronology follows (younger to older):

Normal faulting; the episode described in this paper. Faulting probably occurred during several intervals of Quaternary time, but glaciation has modified or obscured all but the youngest fault scarps in most places.
Minor sedimentation in local traps
Pinedale glaciation
Minor sedimentation in local traps
Extrusion of rhyolite flows constituting upper surfaces of Madison and Pitchstone plateaus
Minor sedimentation in local traps
Bull Lake glaciation
Minor sedimentation in local traps
Buffalo glaciation
White lacustrine and fluviatile strata, deposited in local downfaulted or downwarped basins
Complex interval of faulting, volcanism, erosion, deposition, and possibly glaciation; sequence of events and their dates are not adequately determined; they could be Pliocene or Pleistocene.

Major lithologic units of Tertiary age in and south of Yellowstone National Park are:

Pliocene
  Rhyolite welded tuff, flows, and rhyolitic pyroclastic rocks; intertongues southward with middle Pliocene Teewinot Formation
  Tower Creek Conglomerate; basalt flows
Miocene
  Colter Formation; comprises a thick sequence of green and red mafic pyroclastic and igneous rocks 4 miles south of southwest margin of

Yellowstone National Park; may be equivalent to some basalt and andesite flows within the Park

Oligocene

"Late basic breccia" and underlying "late acid breccia," both of which appear to intertongue southeastward with Wiggins Formation

Eocene

"Early basalt flows"

"Early basic breccia"

"Early acid breccia"

Unnamed sequence of variegated claystone, sandstone, and conglomerate, northwestern Yellowstone National Park.

Paleocene

Pinyon Conglomerate.

Mirror Plateau Fault System

The Mirror Plateau fault system (Figs. 1, 3; Pls. 1, 2) consists of 60 or more northwest-trending normal faults, none of which has previously been mapped. Rocks range in age from late Eocene to Pliocene or possibly younger.

The "early basic breccia" (Iddings, 1896, p. 6; Hague, 1904) is the oldest pyroclastic sequence involved in faulting in this area. These rocks consist of volcanic breccia and conglomerate, composed of dark-green and brown pyroxene andesite and basalt fragments, interbedded with gray and green tuffaceous strata containing petrified trees and fossil leaves that are generally considered to be of late Eocene age. These rocks crop out along the northern and eastern margins of the area shown in Figure 3.

Overlying the "early basic breccia" are the "early basalt flows," which consist of dark-green to black dense hard basalt. At Locality A of Figure 3 (detail shown on Pl. 3 Fig. 1), the basalt is on the upthrown block and forms an escarpment about 100 feet high. A younger conglomerate, possibly the "late acid breccia," is on the downthrown block. In thin section the basalt is porphyritic and consists chiefly of plagioclase with lesser amounts of pyroxene, red-brown biotite, and magnetite. Hague (1904) mapped broad outcrops of the "early basalt flows" in the northern and eastern parts of the Mirror Plateau, and in the southeastern part of the area shown in Figure 3. The basalts are probably of late Eocene age, on the basis of comparison with similar basalt flows in the Tepee Trail Formation of late Eocene age in the Absaroka Range to the southeast.

Iddings (1896, p. 6) described the "late acid breccia" overlying the "early basalt flows," as consisting of light-colored hornblende-mica andesites with some fragments of mafic andesite. Hague (1904) mapped "late acid breccia" southeast of Mirror Lake and along the southern border of the area included in Figure 3. This sequence may be correlative with part of a similar sequence containing Oligocene fossils at Locality D of Figure 1 (Love, 1956a, p. 88).

Rhyolite flows and welded tuffs unconformably overlie all older rocks and consist of red and brown pumiceous to glassy rock with abundant vesicles, fragments of obsidian, and phenocrysts of quartz and plagioclase (Iddings, 1899, p. 391). On a fault scarp directly east of Mirror Lake (Fig. 3), the rhyolite is fine-grained, dense, porphyritic, and shows flow structure. Similar-appearing rhyolites and welded tuffs in the southern part of Yellowstone National Park extend southward into Jackson Hole and intertongue with the Teewinot Formation of middle Pliocene age (Love, 1956c, p. 1909; Houston, 1956, p. 133–139).

Either interbedded with or lying on the rhyolites in several places are light-colored tuffaceous deposits of unknown age, probably either Pliocene or Pleistocene. North of Wapiti Lake (Fig. 3) are extensive white, hot-spring deposits. In most places the rhyolite supports a dense growth of trees (Pl. 1), whereas both older and younger rocks support sparse trees.

Most of the faults cut only rhyolite flows and rhyolitic welded tuff in the area shown on Figure 3. The magnitude of displacement on the ice-scoured surface ranges from less than 20 feet to more than 350 feet. In general, the faults in the western part of the area, especially northwest and about 2 miles east of Wapiti Lake, have the greatest amount of displacement (Pl. 2, figs. 1, 2). The northeast block is downdropped along about two-thirds of the faults, but there are also many conspicuous grabens and horsts. Inclination of fault planes is rarely determinable but is probably steep.

Ice moved southwestward across broad saddles in the Mirror Plateau, and many southwestward-flowing tributaries to Broad Creek and Deep Creek were established along ice-cut valleys. Quaternary faults cut nearly at right angles across these valleys and, depending on the direction of fault displacement, have ponded, offset, or oversteepened the stream channels. Mirror Lake, 1400 feet along, and Wapiti Lake, 2000 feet long, were formed in this manner (Fig. 3).

Hot springs emerge along many fault planes. They are most abundant and conspicuous in the area northwest, north, and northeast of Wapiti

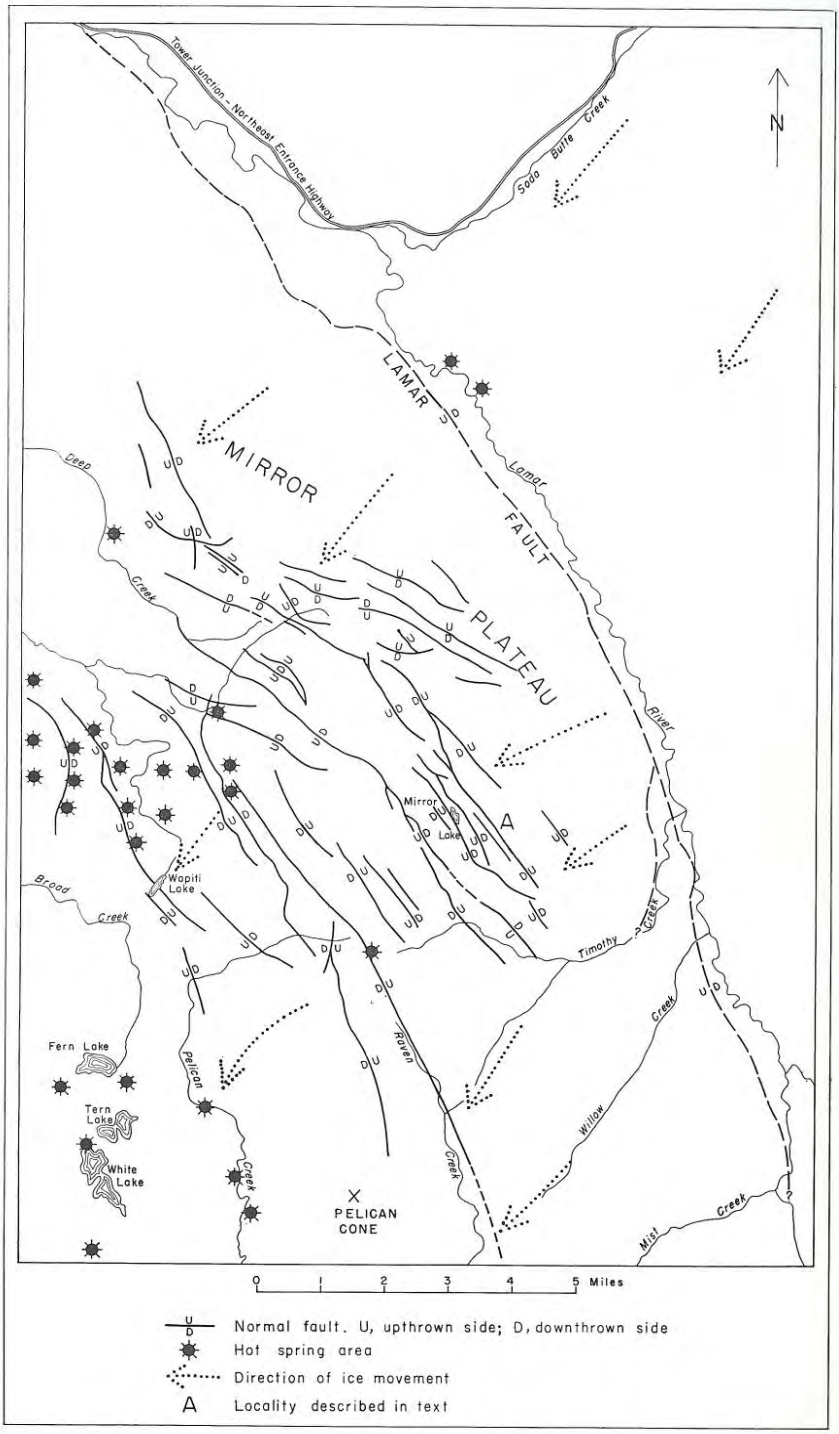

Figure 3. Lamar and Mirror Plateau faults

Lake (Pl. 2, fig. 2). Springs are most numerous in the general area of greatest fault displacement.

Most of the fault scarps appear to be fresh and undissected, although a few have rounded crests. Even some of the freshest support fairly large trees. A fresh scarp is moderately well exposed about a mile east-southeast of Mirror Lake (Fig. 3, loc. A; Pl. 3, fig. 1). Displacement of the ice-scoured surface is at least 100 feet,

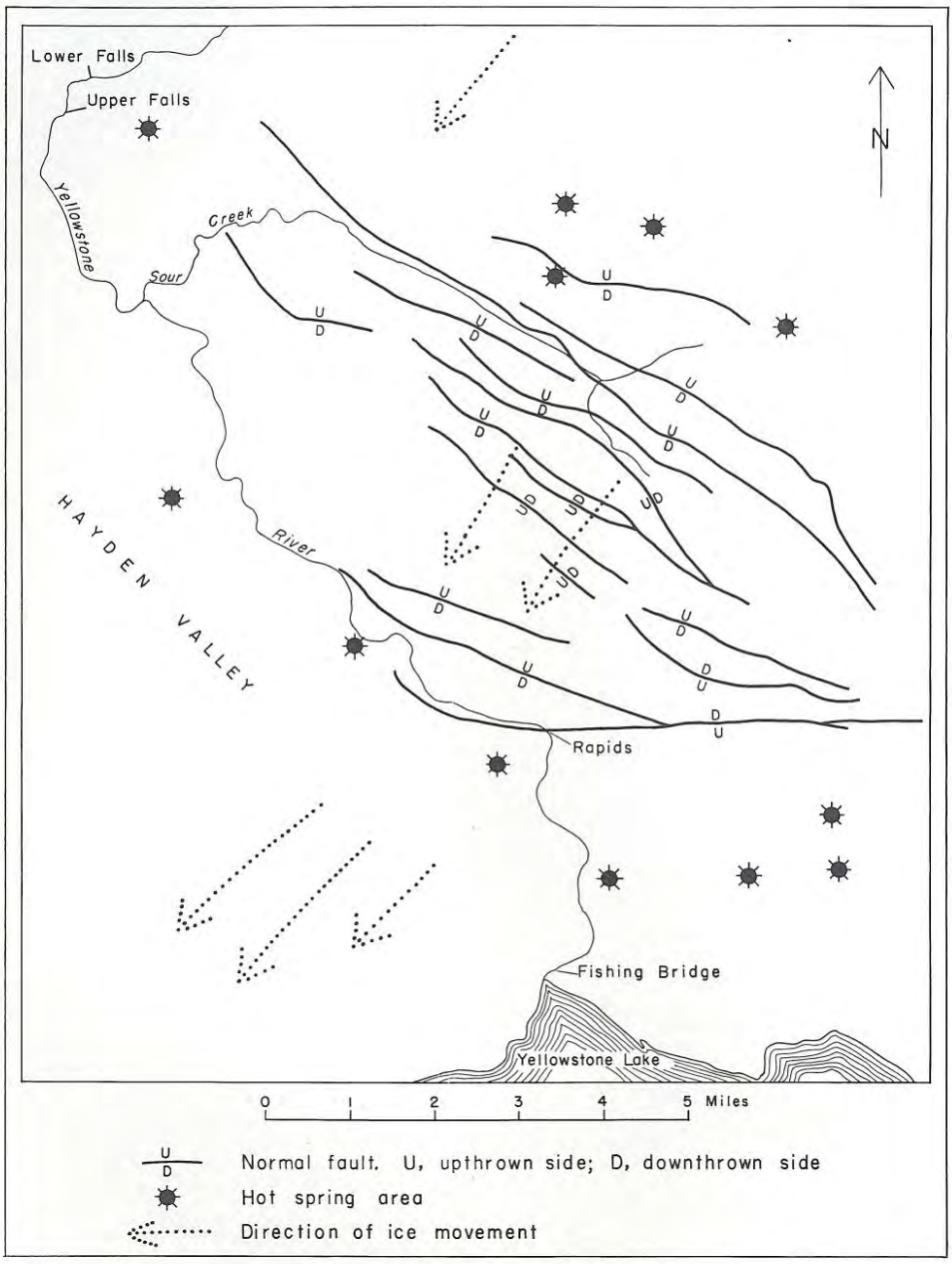

Figure 4. Yellowstone Falls fault system

and total displacement on the fault may be considerably more. Basalt is on the upthrown block. The downthrown block comprises horizontal beds of relatively fine-grained volcanic conglomerate of uncertain age and correlation, possibly the "late acid breccia." The conglomerate is composed of angular to rounded fragments of gray to reddish porphyritic andesite. In the one thin section studied, plagioclase and red-brown biotite are the only phenocrysts.

Inasmuch as the configuration of scarps ranges from fresh and angular to rounded, it is logical to assume that in the Mirror Plateau fault zone recurrent movement has gone on, perhaps from preglacial post-Pliocene rhyolite time to Recent. The faults shown on Figure 3 are those along which there was displacement during Quaternary time.

Lamar Normal Fault

The Lamar normal fault (Fig 3; Pl.1), although poorly exposed, is one of the longest (more than 20 miles) and may have one of the largest displacements (1300 feet or more) of the normal faults in Yellowstone National Park. Howard (1937, p. 71–74) inferred its presence partly on the basis of displaced or missing rock sequences and partly on physiographic evidence. Approximately the same stratigraphic units are present as are on the Mirror Plateau, except for some post-rhyolite basalt that crops out along the floor of the Lamar valley. The Pliocene rhyolite and rhyolitic welded tuff on the northeast block appear to have been down dropped as much as 1300 feet with respect to the southwest (Mirror Plateau) block. The age of the major movement is not known. Howard comments on the freshness of the scarp; however, some broad valleys, interpreted by the writer as having been cut by ice, extend from the upper part of the scarp toward the southwest across the Mirror Plateau. Some of the movement along the Lamar fault probably was late Tertiary, but if the differential elevation of ice-scoured surfaces cut on the rhyolite on the upthrown and downthrown blocks is significant, there may have been as much as 1000 feet of movement during the Quaternary.

Yellowstone Falls Fault System

The Yellowstone Falls fault system (Fig. 4) is about 7 miles southwest of the Mirror Plateau fault system and has not previously been described or mapped. The faults are longer (as much as 9 miles), fewer in number (16), have more displacement, and their scarps are more rounded than those on the Mirror Plateau. The Yellowstone Falls faults lie within an area 6 miles wide and 12 miles long, extending southeastward from a point about 2 miles southeast of the Upper Falls of the Yellowstone River. The faults are normal, appear to have nearly vertical planes, and the northeast blocks along about half the faults are downdropped.

The faults cut rhyolite and welded tuff of Pliocene or early Quaternary interglacial age. The age assignment of the rhyolite is based on the following pollen and spores, collected from the fine-grained diatomite, claystone, and tuff overlying the main mass of rhyolite on the east side of the canyon between the Upper Falls and Lower Falls of the Yellowstone River (identified from seven sediment samples from U. S. Geological Survey Paleobot. loc. no. D1212, by Estella B. Leopold, written communication, 1960):

Trees:
Abies cf. *A. lasiocarpa*
Abies cf. *A. concolor*
Picea cf. *P. engelmanni*
Tsuga cf. *T. mertensiana*
T. cf. *T. heterophylla*
Pinus spp.
cf. Taxodiaceae
Quercus

Shrubs:
Betula
Alnus
Salix
Chenopodiaceae: *Sarcobatus vermiculatus*
cf. *Chenopodium album*
Compositae: *Artemisia* spp.
cf. *Ambrosia*
cf. *Chrysothamnus*
Ephedra cf. *E. nevadensis*
E. cf. *E. torreyana*

Herbs:
Caryophyllaceae: *Stellaria*
Polemoniaceae: *Polemonium*
Polyganaceae: *Eriogonum*
Onagraceae: *Oenothera*
Epilobium
Typha latifolia
Cyperaceae cf. *Scirpus*
Gramineae

Fern allies:
Lycopodium, L. complanatum group
Selaginella cf. *S. densa*

Algae:
Botryococcus
Pediastrum
diatoms, undet.[1]

Pollen of sage and pine predominate in these collections.

Displacement along several faults in the Yellowstone Falls fault system is as much as 300 feet, and on one fault there apparently was more than 600 feet of movement, some of which preceded the most recent glaciation. The last ice mass to occupy this area moved southwestward and cut giant grooves across rhyolite fault blocks that were beginning to rise. After the ice melted, the southwestward-flowing tributaries to the Yellowstone River flowed in these grooves. Renewed faulting, however, prevented most of these tributary streams from maintaining their courses across the rising fault blocks and caused diversion to the northwest along northwest-trending fault valleys. Thus, a rectilinear pattern was developed, with abandoned giant ice-cut grooves and stream-cut valleys extending at right angles across rounded glaciated fault-scarp ridges of rhyolite. Some of the grooves and abandoned stream channels are displaced vertically 200 feet or more, and this is interpreted as a rough measure of the magnitude of fault movement after the last ice melted in this area.

One fault crosses the Yellowstone River 3 miles north of Yellowstone Lake (Fig. 4), where the river is diverted westward, at right angles to its upstream course. Rapids are present along the fault trace (Pl. 3, fig. 2), and the rhyolite exposed on the downthrown side in the river bank is highly fractured. Some hot springs are present in the vicinity of the faults but are not so closely coincident with the fault traces as in the Mirror Plateau area.

White lacustrine and fluviatile strata, which characteristically support little vegetation in Hayden Valley, (Fig. 1; also Howard, 1937, p. 92–100) do not extend north of the Yellowstone Falls faults. The relationship of these strata to the faults has not been determined. Howard concluded (1937, p. 98) that the white sediments are younger than the glacial ice and were deposited in a lake (Howard's Hayden Lake) blocked from flowing north by remnants of the major ice mass. The lake in which the white strata were deposited may also have been formed in part by downwarp of Hayden Valley and in part by rising fault blocks in the Yellowstone Falls fault system that blocked or inhibited drainage to the north.

Solfatara Fault System

The Solfatara fault system (Fig. 5) is about 8 miles northwest of the Upper Falls of the Yellowstone River and has not previously been described or mapped. The present study only delimited a few of the most important faults; many others are present. They range in length from 2 to 10 miles, trend northwestward, and in most the northeast blocks are downdropped. Displacements commonly range from 40 to 120 feet, with a maximum of 200 feet. All the faults cut Pliocene rhyolite except the easternmost, which cuts some "early basic breccia." Extensively decomposed obsidian welded tuff crops out on the Solfatara Plateau. Considerable thermal activity is present in the vicinity of the Solfatara faults, but vents have not been mapped in sufficient detail to determine if the activity is related to the faults.

Ice moved southwestward across most of the Solfatara Plateau, but coalescing and crossing of undrained channelways suggest that ice masses from the north and east were competing for position along the western and southern margins of the area. The dominant postglacial drainage was southwestward, and this has been disrupted by the northwest-trending faults. Ice Lake, Wolf Lake, and Grebe Lake (Fig. 5) probably were formed by ponding of streams against rising fault scarps.

Hering Lake Fault System

The Hering Lake fault system (Figs. 1, 6; Pl. 4) is at the north end of the Teton normal fault. The most clear-cut evidence of faulting is along the west side of Hering Lake. The southern part of this system is shown on the Teton County geologic map (Love, 1956d); other than this, no published maps show these faults. The faults are confined to rhyolitic welded tuff which intertongues with white pumicite and tuff of the middle Pliocene Teewinot Formation. Displacement on the middle part of each of the main faults is about 150–200 feet (Fig. 6), with the east blocks downdropped.

Ice moved southwestward across this area,

[1] After this paper was submitted for publication, a report was received from K. E. Lohman, listing 35 genera and species of diatoms identified from these samples. He considers the diatoms to be of Pleistocene age.

as is shown by scour lines and erratics of lithologic types known only from localities to the east-northeast. Falls River and its tributaries were established on this surface and were subsequently ponded or offset by fault blocks that rose across their channels. Beula, Hering, and South Boundary lakes were formed in this way (Fig. 6; Pl. 4). The fault scarps are straight, vertically angular, and unmodified; they are covered with a heavy growth of timber.

Along the eastern margin of the area shown in Figure 6, Polecat Creek divides, with one part flowing south and another part seeping eastward into Crawfish Creek; these relationships suggest Recent faulting. However, in that locality any Recent fault scarp would probably

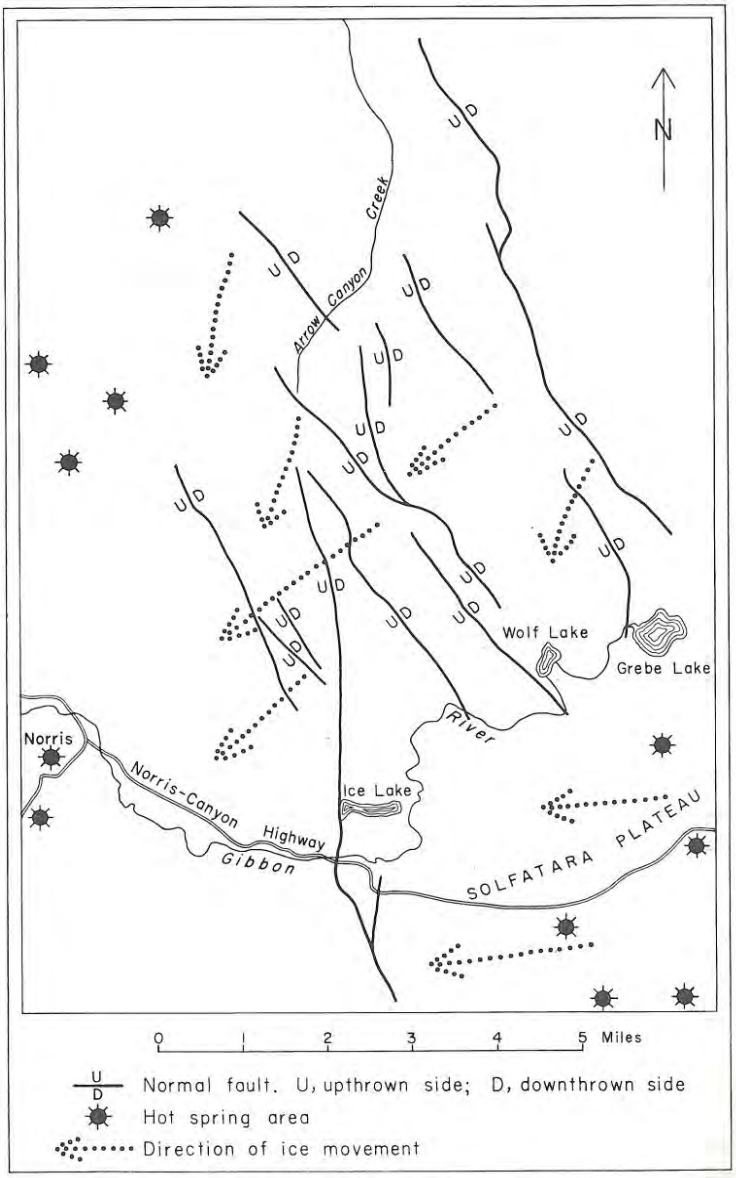

Figure 5. Solfatara fault system

parallel a glacial scour face cut in rhyolite and rhyolitic welded tuff along the southeastern margin of the Pitchstone Plateau. Such an orientation, coupled with relatively poor exposures, makes it difficult to distinguish a fault scarp from an unfaulted ice-scoured scarp. At the base of a scarp directly west of Polecat Creek (Fig. 6) is a row of 15 hot springs whose positions may be governed by a fault.

After the Hebgen earthquake of August 17–18, 1959, Crawfish Creek and Polecat Creek were turbid with yellowish-white mud. Polecat

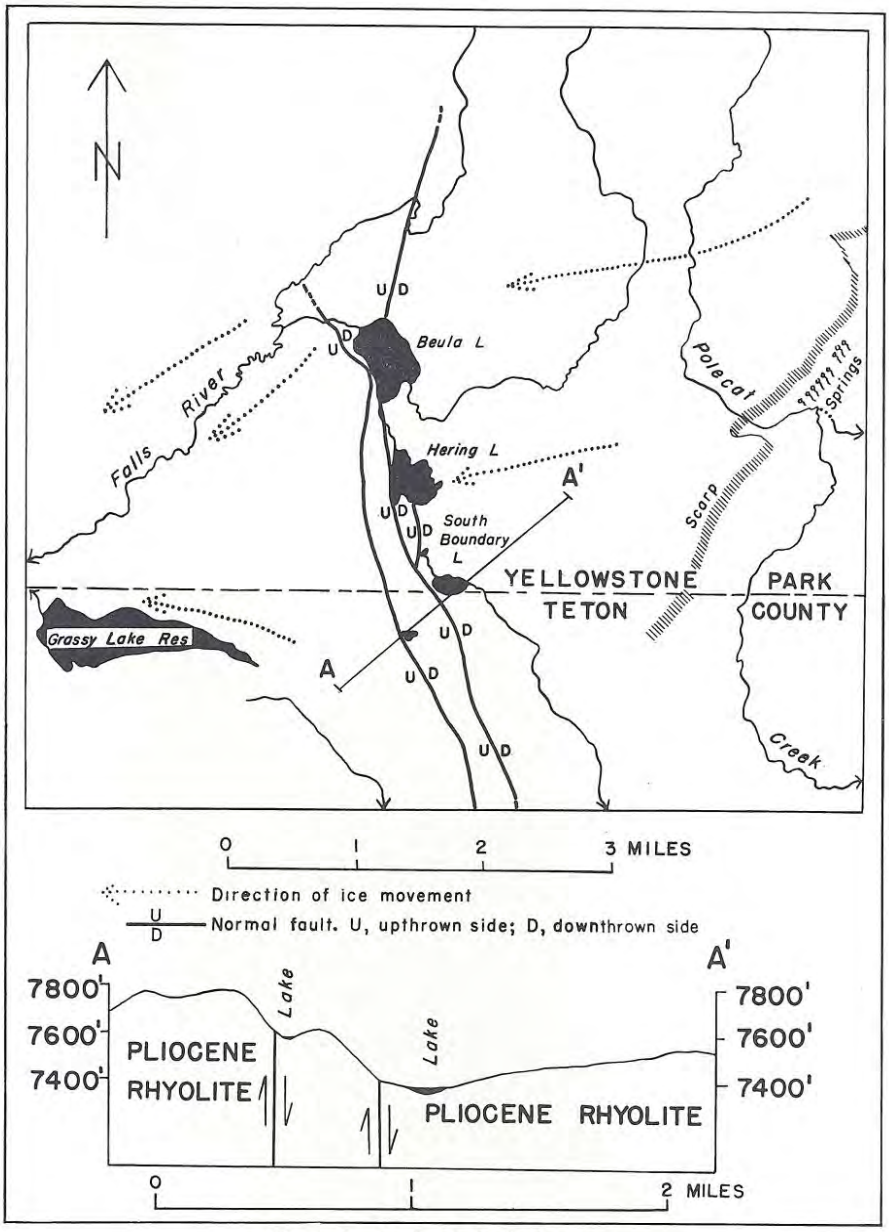

Figure 6. Hering Lake fault system

Creek continued to be turbid for several weeks, and the mud discolored the northern half of Jackson Lake, into which Polecat Creek empties. Several geologists who flew over the hot-spring area along the scarp reported greatly increased thermal activity. There was no opportunity to search for new scarps on the ground.

Probable Faults in Inadequately Studied Areas

Air photos show a number of areas of probable faulting that were not examined on the ground or were inadequately studied. One area (Fig. 1, loc. E) is a northwest-trending zone beginning about 2 miles southeast of Mount Holmes and extending southeast for about 5 miles to a point 4 miles northwest of Norris. Rocks in this area are chiefly upper Cenozoic rhyolite. Northeast blocks are downdropped along rounded scarps. Prominent glaciated valleys trend south-southwest across this zone (Fig. 2, loc. E). The valleys contain numerous erratics of Precambrian granite that probably came from the Beartooth Mountains. Precambrian rocks are exposed in the Gallatin Range to the northwest, but any ice bringing erratics from that direction would have moved nearly at right angles to the valleys and would certainly have modified them. Faults have not offset these valleys extensively, so most of the movement along the scarps apparently preceded the advance of this ice mass.

Another area of probable faulting (Fig. 1, loc. F) is about 2 miles west of the Gibbon Geyser Basin in dominantly upper Cenozoic rhyolite. Lineations on areal photographs trend north and north-northwest across ice-scour lines. The amount of postglacial movement appears to be small.

COMPARISON OF LOCAL EARTHQUAKE EFFECTS WITH THOSE FROM MAJOR HISTORIC EARTHQUAKES

Heck and Eppley (1958, p. 44–57) listed 9 earthquakes in northwestern Wyoming between 1856 and 1956. Woollard (1958, p. 1138) described 11 in the same area prior to 1938 and 7 more between 1938 and 1957. Some were multiple shocks, and one consisted of a long series of shocks (August 24 to December 22, 1930) (Heck and Eppley, 1958, p. 54). Two earthquakes of moderate intensity are listed as having occurred in Yellowstone National Park prior to the Hebgen earthquake of August 17–18, 1959. Blackwelder (1926, p. 196), Fryxell (1933), and Gale (1940) described earthquake shocks in Jackson Hole.

Byerly (1942, p. 80–102) and Davison (1936) discussed the great earthquakes of the world. The Indian earthquake of 1897 resulted in a maximum vertical crustal displacement of 35 feet, and the Mino-Owani earthquake of 1891 in Japan in a displacement of 20 feet. During the Kwanto earthquake of 1923 in Japan a maximum sinking of one part of the adjacent Sagami Bay was 690 feet, and an uplift of another part was 820 feet; it is not known how much of this movement was due to shifting of loose material and how much to tectonic deformation (Byerly, 1942, p. 101). During an earthquake in 1692, the seaward margin of Port Royal, Jamaica, subsided 30 feet (Link, 1960, p. 166–167). Most of the faults developed at the time of the Hebgen earthquake have less than 20 feet of displacement.

CONCLUSIONS

Faults along which there has been 100–300 feet or more displacement in Quaternary time are present in several parts of Yellowstone National Park. There is no way to determine how much displacement occurred in a single episode, but the sharp angular unstepped appearance of several scarps 50–150 feet high (Pls. 1, 4) suggests that each was formed by one major uninterrupted movement. This amount of movement is comparable or greater than that occurring during some of the major historic earthquakes of the world, and considerably greater than that along faults associated with the Hebgen earthquake.

The past history of faulting and earthquake activity in the Yellowstone National Park region, suggests that similar activity of significant magnitude can be expected in the future. Taking proper cognizance of this, tourist facilities and permanent installations can be located in areas safe from rock slides and constructed on bedrock, with adequate structural designs that will insure a minimum of earthquake damage and loss of life.

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Figure 1. Fault scarp southeast of Mirror Lake. Displacement is about 100 feet. Upthrown block is composed of "early basalt flows", and downfaulted valley floor is of conglomerate, possibly "late acid breccia."

Figure 2. LeHardy's Rapids in Yellowstone River along trace of fault in Yellowstone Falls fault system. Horizontal rhyolite is exposed in river bed and on far bank above rapids.

FAULT SCARPS IN THE MIRROR PLATEAU AND
YELLOWSTONE FALLS FAULT SYSTEMS

LOVE, PLATE 3
Geological Society of America Bulletin, volume 72

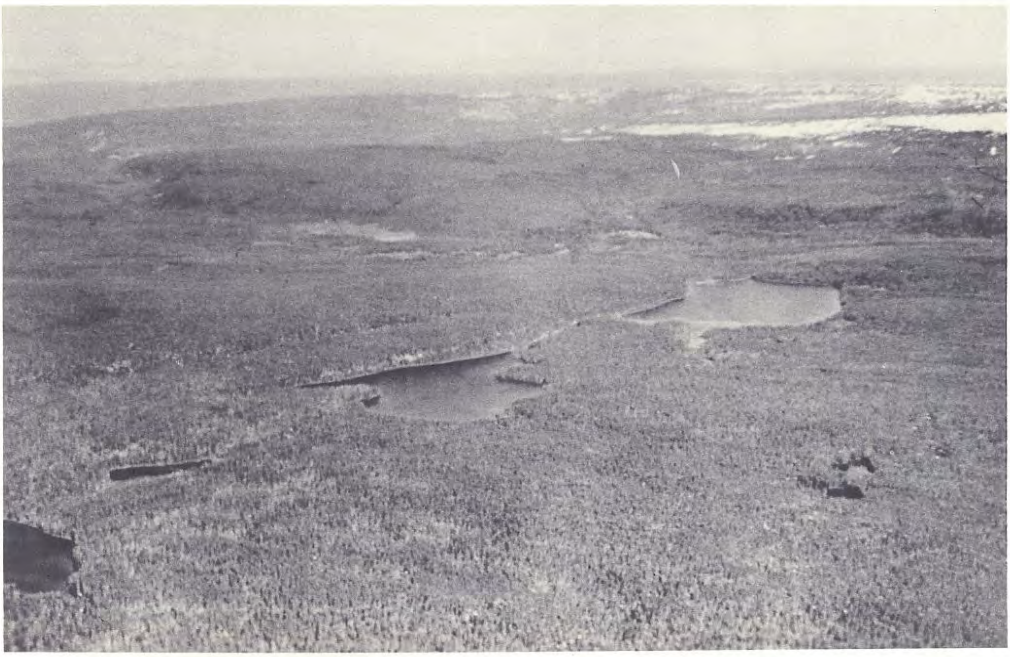

Figure 1. Air oblique photo showing Hering Lake faults. View looking northwest shows straight-line scarp along west side of Hering Lake (center) and a second scarp farther west in trees. Photo by W. B. Hall and J. M. Hill

Figure 2. West shore of Hering Lake showing cliffs and wooded slope along fault scarp of rhyolite that rises 150 feet above lake

FAULT SCARPS IN THE HERING LAKE FAULT SYSTEM

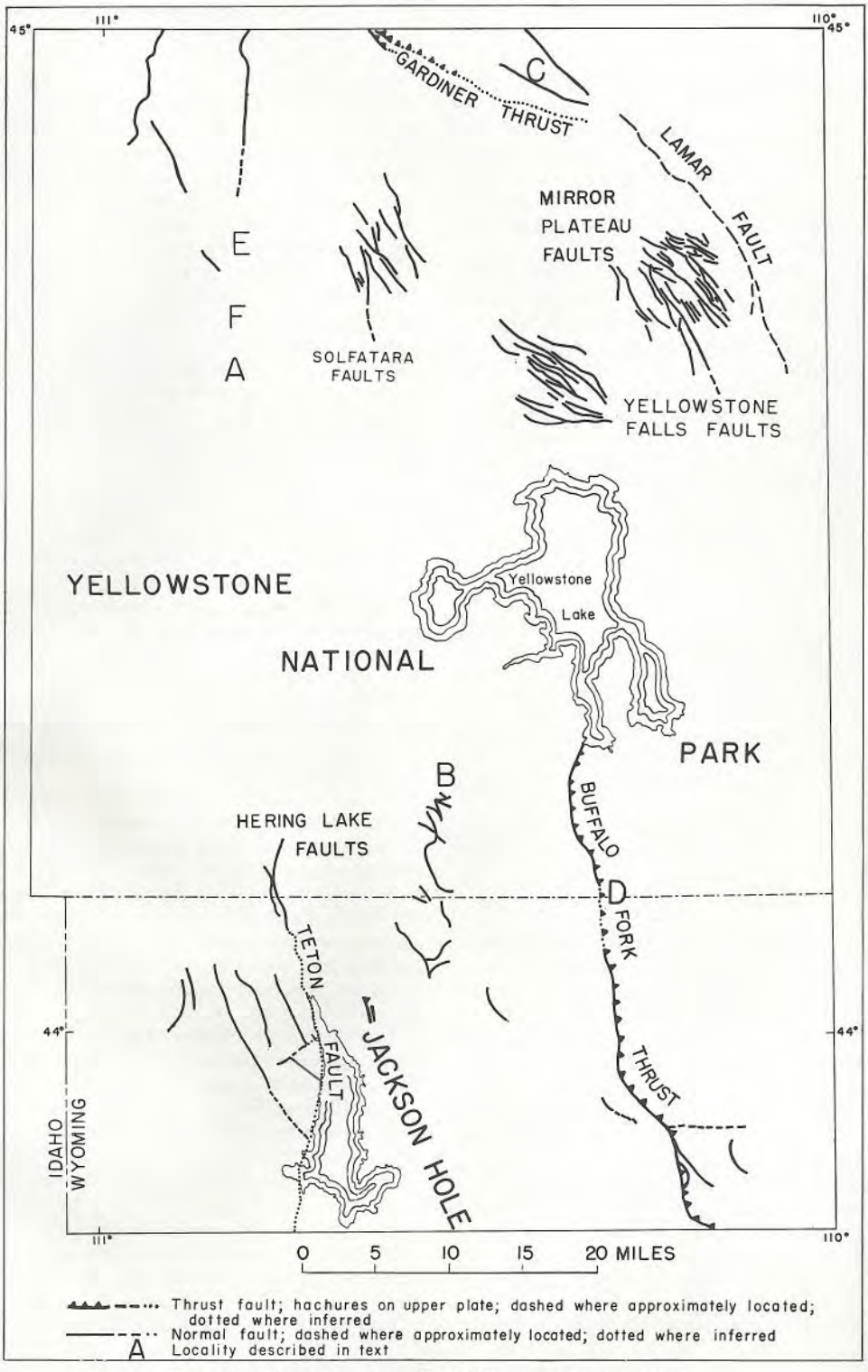

Figure 1. Faults in and south of Yellowstone National Park

two large areas of rhyolite extruded during an interglacial stage and not subsequently covered by ice.

Several times during the Pleistocene epoch, ice accumulated and moved westward, southwestward, or southward across the area shown in Plate 2. Inasmuch as the distribution pattern of the ice changed from one stage to another, the scoured bedrock surface is of different ages in different places. At many localities, this surface was subsequently offset by faults.

Directions of ice movements were determined by ice grooves, scour lines, and erratics of known source. A knowledge of direction of ice movement is in some places essential to recognition of Quaternary faults. For example, in areas of poor exposures, the steep side of an ice-cut valley is difficult to distinguish from a Quaternary fault scarp if they are parallel, but, if they are at right angles, fault offsets of the scoured bedrock surface are more readily apparent.

Holmes (1881) first recognized that a large ice mass once covered much of Yellowstone National Park. Later (1883, p. 55) he stated:

> "It takes no great effort of the imagination to picture the whole Park Plateau covered with a mass of snow and ice—a great *nevé* field fed by the accumulating snows from the surrounding highland, and extending its numerous ice tongues far out to the south and west, forcing them across the ocean divide into the Snake River Valley, or into the headwaters of the Missouri."

Weed (1893, p. 14) named the northern part of the ice mass the Yellowstone glacier. Hague (1896, p. 3) called the ice that moved southward into Jackson Hole the Snake glacier.

Howard (1937, p. 81–147) made a detailed study of glaciation in Yellowstone National Park, and the data supplied by him have been invaluable in all subsequent studies. He described and named the Lamar and Upper Yellowstone glaciers but did not discuss how they correlate with glacial stages in Jackson Hole.

Blackwelder (1915, p. 321–333) first named the Buffalo and successively younger Bull Lake and Pinedale glacial stages. The type locality of the Buffalo stage is along the eastern margin of Jackson Hole. This stage represents the most widespread accumulation of ice in the Jackson Hole area and is generally regarded as pre-Wisconsin. Older glaciation may have occurred but has not been definitely recognized.

The next younger stage is the Bull Lake, which is restricted to canyons and adjacent major valleys in Jackson Hole, but apparently was much more widespread in Yellowstone National Park. The extent of these deposits in the Park has not been determined. They may be of Wisconsin age. Carbon from a laminated silt apparently trapped behind a Bull Lake moraine in Jackson Hole has an age of about 27,000 years (Love, 1956b, p. 149). The moraine is certainly somewhat older.

The Pinedale glacial stage is the youngest in Jackson Hole and is restricted to canyons and valley floors adjacent to the high mountains. The ice of correlative age in Yellowstone National Park was more widespread, but its boundaries have not been determined.

Most of the glaciation above the 9000-foot contour shown on Figure 2 probably represents Blackwelder's Buffalo glacial stage, for that was the time of thickest and most widespread ice accumulation for which there is definite evidence in this region. During the younger stages, ice was thinner and less extensive, and in most places the maximum upper surface of accumulation was below 9000 feet.

The record of glaciation along the western margin of Yellowstone National Park has not been studied in detail. Hall (1959) recognized two and possibly three glacial stages in the Gallatin Range (Fig. 2, loc. G). During the earlier of these, ice was very thick and extensive and probably represents part of the Buffalo glacial stage.

Thick widespread rhyolite flows emerged from vents on the Madison Plateau (Fig. 2, loc. H) and spread westward beyond the west edge of Yellowstone National Park. The major flow mass overrides moraines thought to be part of the Bull Lake glacial stage (G. M. Richmond, written communication, 1959). The margins of the flow mass are, in places, modified by minor glaciation, probably of the Pinedale glacial stage.

The Pitchstone Plateau (Fig. 2, loc. I), in the southwestern part of Yellowstone National Park, is likewise composed of an interglacial rhyolite-flow sequence. Large glacial grooves, probably cut by ice of the Buffalo or Bull Lake glacial stages, extend from beneath the rhyolite on the southwest side of the Plateau, near the head of the east fork of Mountain Ash Creek (Fig. 2, loc. J). The margins of the Pitchstone flows have been modified in a few places by minor glaciation, probably of the Pinedale glacial stage.

Fryxell (1930, p. 1–125), Horberg (1938, p.