SEISMICITY AND THE POSSIBILITY OF EARTHQUAKE RELATED LANDSLIDES IN THE TETON-GROS VENTRE-JACKSON HOLE AREA, WYOMING

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ABSTRACT

Jackson Hole, Wyoming, is a high intermountain valley bounded on the west by the impressive Teton fault, along which the famed Teton Range was uplifted. About 9 km of vertical displacement has occurred along this fault during late Cenozoic time, and some Quaternary alluvial fans are displaced as much as 50 m. Historic accounts indicate sporadic earthquake activity from the time of early settlement, around 1870, to about 1933, and lesser activity continuing to the present. Regional seismicity from about 1950 to 1973 indicates moderate earthquake activity in the Gros Ventre Range as well as scattered events throughout the southern Teton area, but there has been little historic activity along the Teton fault. Several widespread zones of earthquakes were located by detailed earthquake surveys in 1974 and 1975 in the Gros Ventre Range and in the Mt. Leidy Highlands east of Jackson Hole. These active seismic zones coincide with areas of highly unstable slopes and numerous prehistoric landslides. Residents indicate that the Jackson Hole area was seismically active several years before the 1925 Lower Gros Ventre slide and that numerous small earthquakes occurred in the Gros Ventre Canyon in the spring of 1925. An earthquake, estimated to be of magnitude 3 to 4,* occurred 20 hours before the slide. Although evidence is not conclusive, this earthquake may have triggered parts of the slide into creep by induced liquefaction followed by the massive slide failure.

INTRODUCTION

Detailed earthquake monitoring of the Yellowstone National Park region has been conducted since 1972 by the University of Utah as a means of evaluating the seismo-tectonic patterns around the "Yellowstone hot spot" (Smith and others, 1974; Trimble and Smith, 1975). High-gain portable seismographs have been operated within and around the Yellowstone caldera to determine the distribution of epicenters and their relationship to the tectonic and thermal features. These data were also used to map the directions of the regional stress field by fault-plane solutions. This paper presents the results of three earthquake surveys around the south perimeter of Yellowstone National Park as part of an overall effort to understand the origin, lateral extent, and subsurface characteristics of the Yellowstone hot spot.

SEISMO-TECTONIC SETTING

The Teton Range along the west side of Jackson Hole, Wyoming (Fig. 1), is one of the most spectacular mountain ranges in North America. The high peaks and rugged setting of the eastern front are directly attributable to: (1) relative vertical uplift, about 9 km (Love and others, 1973), of the mountain block with respect to the valley floor along the north-trending Teton normal-fault (Figure 1); and (2) the recentness of this movement, most of which occurred in late Cenozoic time.

The Teton Range is located within the Intermountain Seismic Belt (Smith and Sbar, 1974), a major zone of earthquake activity that extends 1,300 km from Arizona through Utah, eastern Idaho, western Wyoming, and western Montana. This major seismic belt separates the Great Basin from the Colorado Plateau and the Rocky Mountains and is thought to represent a zone of elastic decoupling between the stable North American plate to the east and the tectonically active subplates of the western United States (Smith and Sbar, 1974). This seismo-tectonic setting supports the hypothesis that the uplift of the Teton Range was likely accompanied by large earthquakes.

The main stage of Basin-Range tectonism, which generated the present structure and consequently the mountainous topography of the Teton Range, began during late Tertiary time (Love and others, 1973) and has continued sporadically to the present. Quaternary alluvial fans at the base of the Teton Range have been offset as much as 50 m (Love and Montagne, 1956) and loess 12,000-15,000 years old, as much as 45-50 m (Love and Taylor, 1962); these scarps attest to the most recent activity. Love and Reed (1971) showed that uplift along the Teton fault averages 3 cm/100 years and stated that in view of the recent crustal deformation it is not surprising that small earthquakes are frequent in the Teton region.

Contemporary east-west crustal extension, as inferred from fault-plane solutions of earthquakes in the Intermountain Seismic Belt (Smith and Sbar, 1974), is consistent with that documented for the Cenozoic tectonism of northwest Wyoming (Love and others, 1973). However, detailed geophysical measurements in the Yellowstone National Park region, north of the Teton area, show anomalously hot

*Arabic numbers are Richter scale magnitudes; Roman numerals are Mercalli scale intensities.

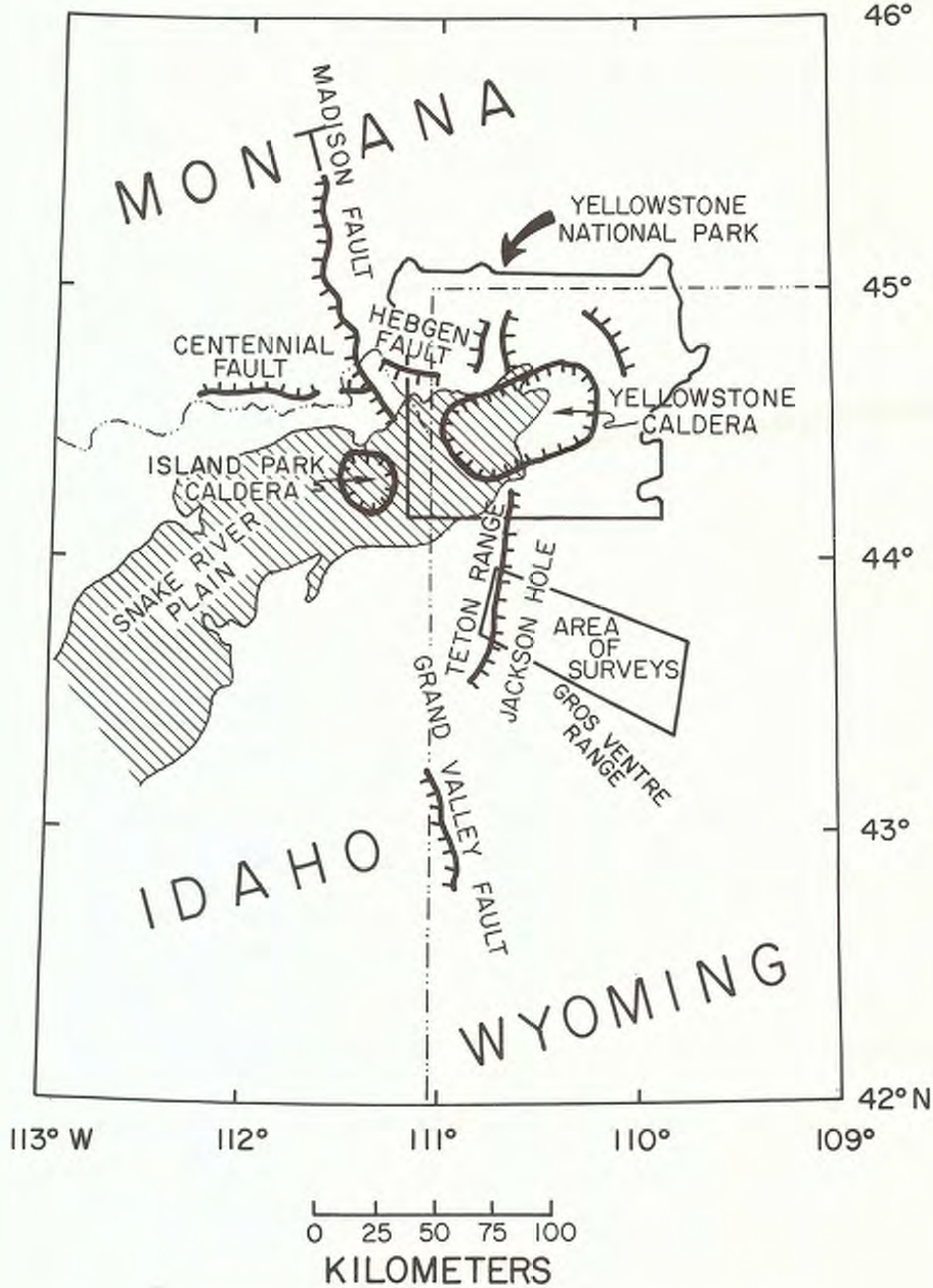

Figure 1. Generalized tectonic map of northwest Wyoming, eastern Idaho, and southwest Montana.

crust, a high level of earthquake activity, and north-south extension west of the Yellowstone caldera (Smith and others, 1974). In the western Yellowstone area, Trimble and Smith (1975) showed a marked N. 80° W. trend of seismic activity along the Hebgen fault zone that intersects the Intermountain Seismic Belt at the Yellowstone caldera. Similarly, normal faults extend north from Jackson Hole (Fig. 1) to the south margin of the caldera. Thus, the Yellowstone region represents a variation in the regional tectonic pattern and may be a junction of both north-south and east-west crustal extension. The Teton region is, therefore, one of the most important areas to provide an assessment of the effects of the Yellowstone hot spot on the surrounding tectonic pattern and on the seismo-tectonic transition between the Basin-Range and the Rocky Mountains.

The Teton area is also tectonically important because it is one of the easternmost zones of extensive normal-faulting in northwestern Wyoming and thus could represent the easternmost area of substantial seismicity of the Intermountain Seismic Belt in this region. Normal-faulting occurs to a lesser extent farther east in the Gros Ventre and Absaroka ranges but lacks the pronounced seismicity found to the north and south along the Intermountain Seismic Belt.

HISTORIC SEISMICITY

Historic seismicity prior to 1962 was defined by the degree of ground shaking described in personal felt reports, using the Modified Mercalli scale of I to XII. Epicenters for this early period were not instrumentally determined and thus were only accurate to ± 30 km. After 1962, instrumental epicenter locations were accurate to ± 10 km.

The earliest documented earthquakes in Jackson Hole consisted of a felt sequence, maximum intensity V, at the mouth of the Gros Ventre Canyon from March 23 to April 12, 1923 (Coffman and Von Hake, 1973). The earliest published discussion of historical earthquakes was given by Blackwelder (1926), who described a slight earthquake felt in Jackson on September 3, 1925. Blackwelder (1926) also indicated that a U.S. Forest Service employee who had lived in Jackson Hole for 40 years described perceptible earth tremors as rather common in Jackson Hole, but that none had been strong enough to produce damage. The Forest Service employee also noted that the shocks were localized; *i.e.*, when there were light shocks at Moran they were not felt at Jackson, 45 km south.

The next account of earthquakes was given by Fryxell (1933), who documented several felt shocks in the Gros Ventre Canyon, January 25-28, 1932. The largest shocks, of intensity VI, caused some minor damage. The most recent documented earthquake sequence (Gale, 1940) consisted of three shocks during the 1939 autumn. These shocks did not produce any damage and, from felt reports, were judged to be near or just southwest of Jackson. The latest significant earthquake, intensity VI, occurred on Feb. 23, 1948, on the west side of the Teton Range but was felt in Jackson Hole.

Love (1973) indicated that during the years 1925, 1928, 1932, 1959, 1968, 1970, and 1972, several earthquakes were felt in the Jackson Hole area. Some of these shocks—for example, the August 17, 1959, magnitude—7.1 earthquake at Hebgen Lake, Montana—occurred 150 km northwest but were large enough to be felt in the Teton area. After about 1933 the relative incidence of felt-earthquake activity in the Teton area perceptibly decreased, and few earthquakes have been reported since. None of the historical accounts of earthquakes suggest that the epicenters were along the Teton fault.

Tabulated earthquakes (Table 1) in the Teton area (NOAA data, 1975) from about 1950 to 1973, for events as small as about magnitude 3.0, are plotted in Figure 2 and show an interesting pattern: (1) the Teton fault zone has had little earthquake activity; (2) the Gros Ventre Range has had scattered activity with moderate magnitude earthquakes; and (3) the area 20-50 km south of Jackson Hole in the Wyoming Range appears to have been moderately active.

MICROEARTHQUAKES

To begin detailed monitoring of earthquakes in the Teton area, two reconnaissance surveys were conducted during 1974. The first survey consisted of four high-gain stations operated along the northern part of the Teton fault during a two-week period in June. Using these closely spaced stations, earthquakes as small as Richter magnitude +0.5 were located within the array. Results of this survey showed only two earthquakes on the Teton fault, despite the fact that two sensitive stations were located directly on the fault trace. However, 11 shallow-focus earthquakes of magnitude +0.5 to +2.5 were located in the Mt. Leidy Highlands north of the Gros Ventre Canyon (Fig. 2).

To demonstrate the accuracy of the epicenters, dynamite blasts were recorded at the site of construction of a new chairlift near the south end of the Teton Range. Their calculated epicenters were within 2 km of their true locations and indicate the accuracy of the epicenter determinations for earthquakes located within one array-radius of the array.

The second reconnaissance survey was conducted in September 1974. A four-station network was centered near the activity located earlier in the Mt. Leidy Highlands. Twenty-three shallow-focus earthquakes were located along a marked north-south zone east of the Gros Ventre Range. Several scattered events were also located in the Mt. Leidy Highlands.

In June and July 1975, a detailed 12-station survey was implemented (Fig. 2) to investigate the active areas detected in 1974 and to extend coverage around the south perimeter of the Yellowstone hot spot. Thirty earthquakes were located north and east of the Gros Ventre Range, but none coincided with any notable fault. A swarm of closely-spaced earthquakes was located on the northwest side of the Mt. Leidy Highlands, and only six small events were located near the Teton fault (Fig. 2).

The scattered earthquake activity throughout the Mt. Leidy Highlands does not coincide with any distinct tec-

TABLE I. TABLE OF HISTORICAL TETON-GROS VENTRE-JACKSON HOLE EARTHQUAKES
(Taken from National Oceanic and Atmospheric Administration data)

No.	Date	Time (GMT) h	m	s	Lat. N	Long. W	Richter Magnitude
1	21 FEB 1951	17	09	56.0	43° 00'	110° 00'	
2	02 SEPT 1959	00	05	05.0	44° 00'	110° 00'	
3	06 OCT 1962	09	28	17.4	43° 36'	110° 48'	
4	25 JUNE 1963	15	51	49.6	44° 00'	110° 00'	
5	12 OCT 1963	06	58	25.7	43° 18'	110° 54'	
6	09 DEC 1963	01	45	18.2	43° 36'	110° 06'	
7	14 DEC 1963	12	55	07.9	43° 36'	110° 18'	
8	28 FEB 1964	01	09	43.1	43° 36'	110° 12'	
9	13 APR 1964	11	36	30.4	43° 18'	110° 48'	3.7
10	02 MAY 1964	03	24	24.1	43° 36'	110° 24'	
11	07 MAY 1964	11	42	30.4	43° 18'	110° 24'	
12	11 JUNE 1966	05	35	51.3	43° 06'	111° 00'	
13	08 OCT 1966	15	29	53.8	43° 12'	111° 00'	
14	27 OCT 1966	17	15	11.0	43° 12'	111° 00'	3.7
15	26 JUNE 1967	22	31	02.8	43° 00'	111° 00'	4.0
16	11 SEPT 1967	04	10	46.5	43° 00'	111° 00'	3.5
17	18 DEC 1967	22	12	50.1	43° 24'	109° 48'	
18	20 DEC 1967	07	13	23.6	43° 48'	110° 24'	
19	16 NOV 1968	03	51	22.4	43° 40'	110° 13'	3.9
20	27 AUG 1969	18	35	18.9	43° 00'	110° 43'	3.9
21	30 AUG 1969	02	01	02.5	43° 04'	110° 40'	3.9
22	21 SEPT 1970	07	04	36.9	43° 11'	110° 46'	4.4
23	24 MAR 1973	23	20	04.5	43° 59'	110° 14'	

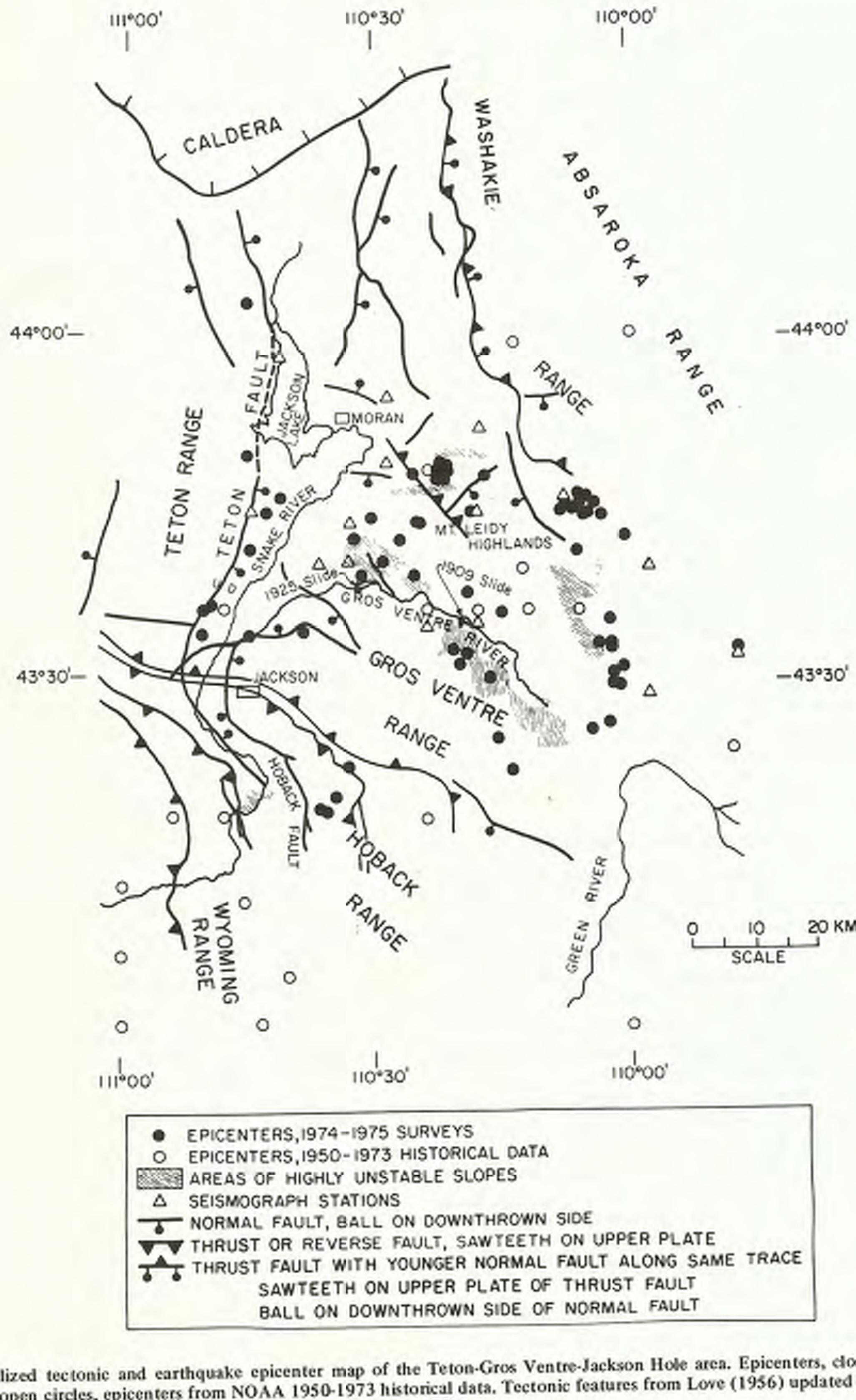

Figure 2. Generalized tectonic and earthquake epicenter map of the Teton-Gros Ventre-Jackson Hole area. Epicenters, closed circles, from 1974-75 surveys; open circles, epicenters from NOAA 1950-1973 historical data. Tectonic features from Love (1956) updated to 1976. Pattern indicates mapped areas of highly unstable landslide areas from Bailey (1972).

tonic or geomorphic feature. Focal depths are shallow, from near surface to 10 km, and indicate fracturing both within the sedimentary sequence and in the crystalline upper-crustal layers.

The north-trending zone of epicenters east of the Gros Ventre Range defines a distinct sequence of earthquakes that is probably related to a tectonic feature. Because the events were located outside the recording array, focal-depth resolution was limited, but the foci appear to be shallow, from near-surface to 15 km. No mapped fault or other known tectonic feature coincides with these earthquakes, but they could represent strain release on a buried fracture zone.

In the South Arm of Yellowstone Lake, 40 km north, a north-trending zone of earthquakes (Smith and others, 1974) coincides with a fault zone at longitude 110° 20′ W. The earthquakes in the eastern Gros Ventre Range occurred near longitude 110° 05′ W., 15 km further east, and suggest the possible continuity of a through-going zone of crustal weakness. Nonetheless, the extent of active seismic zones east of the Teton fault zone is surprising. Possible interpretations of this effect may be a migration of extensional tectonism eastward into the North American plate, or stress relaxation along a pre-existing zone of weakness such as the Wyoming hinge line.

The lack of significant earthquake activity along the Teton fault may be explained by one of the following: (1) our period of observation was insufficient to sample the true state of seismicity, particularly if the activity is episodic; (2) the fault may be relatively "locked" and could be storing strain energy, implying a future large earthquake; or (3) the fault may be inactive and not storing strain energy.

EARTHQUAKE INFLUENCE ON LANDSLIDES

Land stability in the Gros Ventre Range and the Mt. Leidy Highlands has been recognized as an important environmental problem (Love, 1973; Bailey, 1972). Glacial deposits, steep slopes, incompetent surface material, and 50-100 cm of annual precipitation combine to create a potential for major landslides. The role of earthquakes in the landslide mechanism, although not conclusively known, may have been that of seismically induced liquefaction of an unstable slope into failure (Voight, 1976).

The famous Lower Gros Ventre landslide (Fig. 2) of June 23, 1925, is the largest historic landslide in the United States. Here a slide mass of 38×10^6 cubic meters (50×10^6 cu yards) of material (Voight, 1976), greater than the mass of the 1959 Hebgen slide that was triggered by a magnitude 7.1 earthquake, was released on a dip-slope following a heavy spring runoff involving deep water saturation. Photographs taken prior to the 1925 slide show that it overran an older stabilized slide.

The possibility that earthquakes triggered the 1925 Gros Ventre slide and related occurrences has been investigated in an attempt to document the role of earthquakes on landslides in the Jackson Hole-Gros Ventre region. No quantitative evidence of 1925 earthquake epicenters is available because of inadequate seismograph station coverage in the western United States at that time. However, personal accounts documented by Mrs. Elizabeth W. Hayden, a historian of the Jackson Hole, Wyoming area and by the senior author indicate that earthquake activity was abnormally high before and after the 1925 Gros Ventre slide. The following are accounts by various observers:

1) Mr. W. O. Owen, in his papers at the Wyoming State Museum, stated that earth tremors had been felt in Jackson Hole the spring of 1925, including quite severe ones a few days before the slide. (*Jackson Hole Courier*, June 25, July 2, 1925).

> "It is interesting to note here that quite a number of light earth tremors have been felt in the Hole this spring, quite severe one noted (June 21) Sunday and again (June 24) Wednesday. But as to whether the earth tremors or a super abundance of surface water was the direct cause of the slide is unknown."

2) John G. Bartram's article "The Gros Ventre Landslide and Flood," in *The Midwest Review* (Vol. 15, No. 7, 8, July, August, 1927), said much the same thing and predicted more slides, one probably two miles (3.2 km) east of the 1925 slide.

3) State Engineer Frank Emerson quoted Guil Huff, an eyewitness to the slide, in an article in the *Wyoming Tribune* of August 11, 1925, and stated that Mr. Huff questioned several parties living near the slide who said they felt tremors before the slide. Definite tremors were felt to the north two days after the slide.

4) In a reply to a letter from the senior author, dated April 17, 1975, Mr. W. C. (Slim) Lawrence, a long-time resident of Moran, stated:

> "In reference to earth tremors that I have felt in my 50 years of living in the Moran area [with respect to a shock preceding the 1925 Gros Ventre slide]. I can well remember of feeling two shocks [the first shock described here, the second the 1959 Hebgen Lake earthquake]. In old Moran, close to the dam, on the evening of June 22, 1925, about 8 P.M. as I was in the dining room of Teton Lodge. It was strong enough to scare the cook very much, as he came running out of the kitchen. A few dishes fell on the floor and he would not go back in the kitchen that night."

On the basis of this description, the earthquake described by Mr. Lawrence had an estimated Richter magnitude of 3 to 4.

5) Mr. Billie Bierer, a rancher who lived in the Gros Ventre Canyon, replied to Mr. Albert Nelson about a series of running springs on the south side of the canyon:

> "Yes, I have noticed that and cannot see where the water can be going unless it is following the formation between two different stratifications and coming to the surface at some other

water level point. If not, this mountain side would be a mushy, woozy boil. However, it may be there is a wet line running between these strata and the time will come when the entire mountain will slip down into the canyon below. For instance, some of these times these earthquake tremors that are coming so often are going to hit about the right time when the mountain is the wooziest, and down she will come" (Hayden, 1963).

6) Another observer, Mr. Richard Hecox of the Upper Green River Valley, 30 km southeast of the Gros Ventre slide area (Fig. 2), has described to the senior author that earthquakes were frequently felt from 1920 to about 1935. One earthquake, about 1930, was strong enough to throw a person off a tall hayrack in the winter, but because of the sparse population and remote location, the local ranchers did not report the occurrence.

These astute observers, although not formally trained in earth science, provided valuable accounts and perceptive descriptions.

From these reports, it appears that earthquakes in the Jackson Hole area were more common for several years preceding the 1925 Lower Gros Ventre slide than at present. That an earthquake triggered the 1925 Lower Gros Ventre slide cannot be proven, but from the eyewitness accounts of an abnormal increase in earthquake activity before and after the 1925 slide, it is worthwhile to consider the possibility of earthquake inducement.

Voight (1976) gives a plausible scenario of the mechanism of failure for the Gros Ventre slide under the influence of earthquake triggering. In Voight's (1976) interpretation, ground vibration from one or more earthquakes is considered to set into motion a sequence of time-dependent creep events that culminate some hours later in the massive slide release. Voight's sequence consists of: (1) initial, seismically induced liquefaction in limited portions of the slide; (2) subsequent load transfer to fluid pressure, causing shear failure of claystone and sandstone, (3) propagation of failure along the wall boundary, leading to movement of the toe buttress, acting in resistance; (4) propagation of large shear strains that move upslope; and (5) flow and slippage of the entire slide initiating into massive failure as toe resistance is diminished. Thus it is conceivable that the small earthquake felt on the evening of June 22, 1925 by Mr. W. C. (Slim) Lawrence, 20 hours prior to the slide, or even smaller shocks in the Gros Ventre Canyon, as described by Mr. Bierer, may have initiated the unstable slope into a time-dependent failure mechanism that eventually led to the "instantaneous" massive slide. It is important to point out that the triggering mechanism need not be one of time-dependent creep but rather, as in most large slides induced by earthquakes, it is an "instantaneous" shear failure at the base of the slide mass. Likewise, it is equally important to point out that the 1925 Gros Ventre slide could have been initiated without external forces (Voight, 1974, 1976). Seismicity and liquefaction may have been contributing factors to the slide, but they cannot be shown to be necessary for failure. Therefore, the possible effects of seismicity, although documented for the time and general location of the landslide, must remain inconclusive.

An interesting correlation between earthquakes and landslides in the Gros Ventre Range can be seen in Figure 2 where both the epicenters and the areas of highly unstable slopes, shown on the landslide hazard map of the Teton National Forest by Bailey (1972), have been plotted. The pattern in Figure 2 represents areas of active slumps, earthflow and landslide deposits, and oversteepened slopes.

Unpublished mapping by J. D. Love shows more than 100 pre-historic landslides along the Gros Ventre Valley that are in many cases coincident with those areas mapped as unstable by Bailey (1972). Note that the earthquakes north of the Gros Ventre Valley and east of the Gros Ventre Range coincide with or are near the areas of highly unstable slopes. If earthquake triggering for the Lower Gros Ventre slide is a valid mechanism, it suggests the possibility that some of the prehistoric landslides on the north flank of the Gros Ventre Range could have also been related to earthquakes. Voight's (1976) thorough discussion of the mechanism of the 1925 Lower Gros Ventre slide shows that seismically induced liquefaction and subsequent load transfer within liquefaction zones could have caused shear failure of water-saturated claystones and sandstones at the base of the slide. Seismically induced liquefaction in the Intermountain region is not unknown. Smith (1974) has suggested that soil failure by liquefaction in saturated sediments also occurred for the 1934, magnitude–6.5, Hansel Valley, Utah earthquake.

The coincidence of earthquakes before and after the 1925 Lower Gros Ventre slide and the close spatial association of earthquake zones and highly unstable slopes in the Gros Ventre Range suggest an important environmental hazard. Of course, not all landslides in the Gros Ventre Valley were necessarily seismically induced, but if even a small percentage were triggered by earthquakes, the potential hazards remain important. These hazards would relate especially to real estate development, road construction, campgrounds, farming and ranching, ground-water exploration, sewage disposal, and logging.

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