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SEISMICITY OF THE TETON-SOUTHERN YELLOWSTONE REGION, WYOMING

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ABSTRACT

Epicenter patterns, focal depths, and focal mechanisms for earthquakes occurring between 1973 and 1981 in the Teton-Jackson Hole-southern Yellowstone region are presented in this study. Available earthquake information recorded prior to 1980 was combined with the results obtained from two microearthquake surveys operated in 1980 and 1981. Earthquakes used in this joint analysis met rigid standards for location accuracy, and hence the resulting data set provides the most complete, accurate and up-to-date information on seismicity in this region.

The majority of earthquakes in the region do not appear to be associated with mapped traces of Quaternary faults. The Teton fault appears to be active at the small earthquake level along some of its segments, although several segments, including the north-central segment which exhibits the greatest prehistoric displacement, appear to be quiescent. Seismicity in the Gros Ventre Range may be related to reactivation of older basement structures. Fault plane solutions in the region show predominately normal faulting with extension in an east-west to northwest-southeast direction.

Geologic seismic moment rates of 1.1×10^{24} dyne-cm/yr for the Teton region and 4.0×10^{23} dyne-cm/yr for the Teton fault were estimated using available geologic information on mapped faults. From the limited available data, a return period of 130 to 155 yr for a magnitude 6.5 to 7.5 earthquake is predicted for the Teton region, while the Teton fault has a predicted return period of 800 to 1800 yr for a magnitude 7.5 earthquake. A regional strain rate of 6.9×10^{-9}/yr is also obtained.

INTRODUCTION

The Teton-Jackson Hole-Southern Yellowstone region of northwestern Wyoming (Figure 1) forms an important segment of the southern Intermountain seismic belt that extends southward from the Yellowstone volcano-tectonic system. During historic time, this region appears to have been less seismically active than other parts of the Intermountain seismic belt, despite evidence that some faults in the region show Holocene movement (Love and Taylor, 1962). Historic earthquake activity (1870 to 1982) has been limited to scattered, small earthquakes of less than magnitude 4.5. No permanent local seismograph network has been operated in the region. Prior to 1979, instrumental seismicity was determined from earthquakes recorded at near-regional distances on surrounding networks and data recorded in several short-term microearthquake surveys.

As a means of evaluating the detailed seismicity of this region, two microearthquake surveys were conducted during 1980 and 1981. These surveys focused on the Teton fault zone and the Pitchstone Plateau of southwestern Yellowstone (Figure 1). Results of these surveys are combined with data from other microearthquake surveys and regional earthquake information to evaluate the seismicity of the Teton-Jackson Hole-southern Yellowstone area. All earthquakes in the combined data set were relocated using updated velocity models, and only those earthquakes with epicentral location errors of less than ±0.6 km were retained. The resulting data

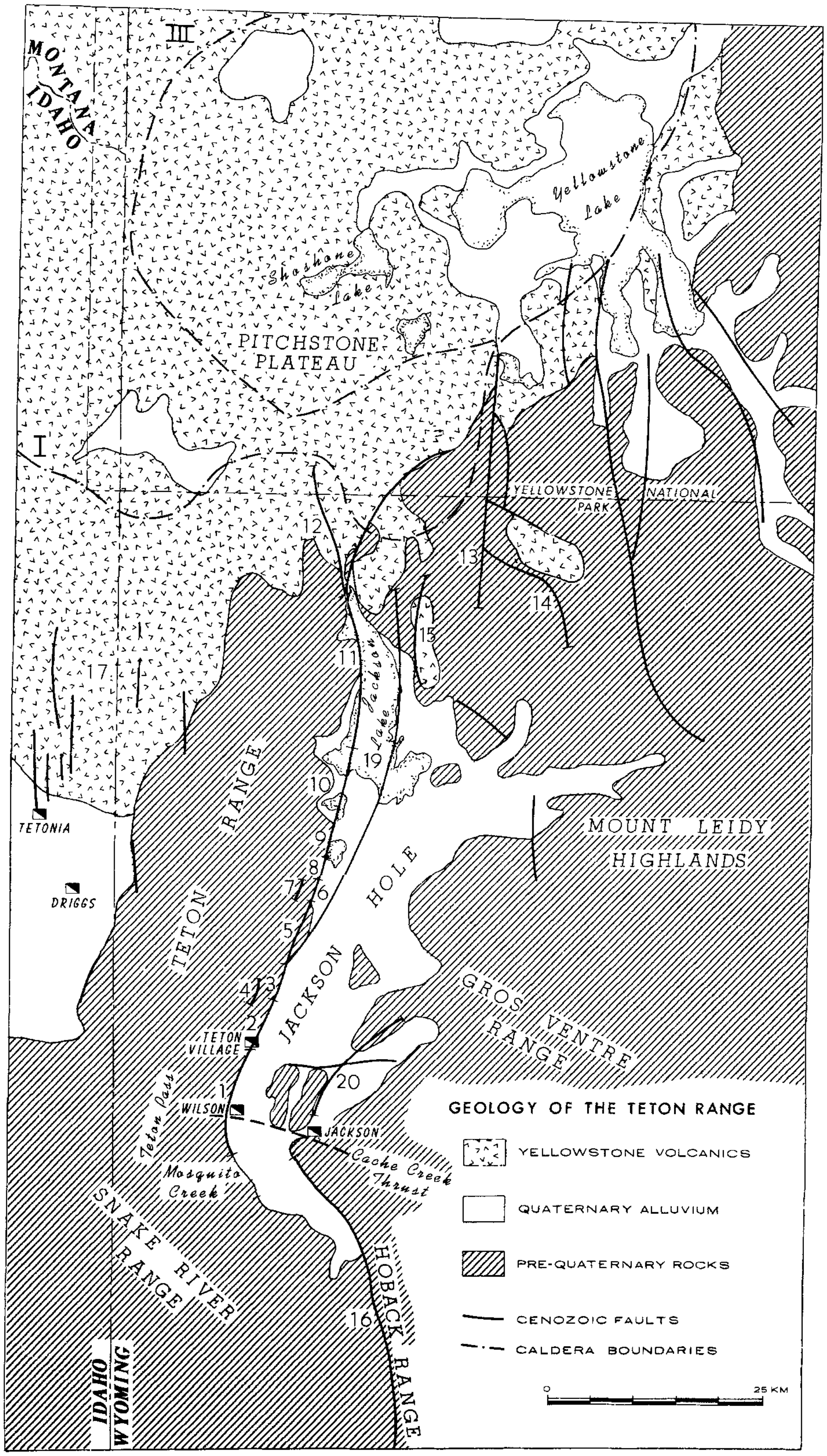


FIG. 1. Generalized geology and Quaternary faulting in the Teton-southern Yellowstone region. Map adapted from Love *et al.* (1973) and the U.S. Geological Survey (1972). Numbers refer to fault segments listed in Table 1. Roman numeral I denotes the 1.9 m.y. old caldera boundary; III denotes the 600,000 yr old boundary.

set provides the most complete and accurate information on epicenter patterns, fault behavior, and focal depth relationships currently available for the region. By using geologic information on Quaternary faulting to determine seismic moment rates in the study area, return periods for $7.0 \leqq M_L \leqq 7.5$ earthquakes are also estimated.

CENOZOIC TECTONICS OF THE TETON REGION

The Teton Range is located at the northeastern limit of Basin and Range block faulting in northwest Wyoming. The Teton fault extends 100 km north-south on the east side of the Teton range, producing a spectacular escarpment on the westward titled fault block that forms the range (Figure 1). Normal fault displacement along the Teton fault was initiated less than 9 m.y. ago with cumulative displacement estimated to be about 10 km (Love and Reed, 1969). Displacements of alluvial fans and glacial moraines at the base of the Teton range provide evidence of repeated movement along the fault during Pleistocene and Holocene time. A maximum postglacial (<14,000 yr) displacement of 24 m has been measured near Bearpaw Bay on Jackson Lake in the north-central part of the fault (Gilbert *et al.*, 1982). Postglacial displacements along the fault have been restricted to the central segment of the fault extending from the town of Wilson to the central Jackson Lake region, an important observation that will be discussed later. There has been about 2130 m of movement along the Teton fault (Gilbert *et al.*, 1982) since the eruption of the Huckleberry Ridge tuff, 1.9 m.y. ago (Christiansen and Blank, 1972). An average late Cenozoic rate of uplift on the fault has been estimated at 3 cm/100 yr (Love and Reed, 1969).

Deformation of Quaternary sediments in the Jackson Lake basin adjacent to the fault has also been documented from seismic reflection profiles recorded by the University of Utah in 1974 (Smith, in preparation, 1983). These profiles reveal that sediments of probable Quaternary age in the western part of the lake basin are generally flat lying; while in the eastern lake basin sediments form a complicated system of east- and westward dipping layers with major angular unconformities. This pattern indicates that a period of late Cenozoic deformation has taken place in the eastern lake basin and may have been related to complex faulting along subsidiary splays of the Teton fault.

The southeastern end of Jackson Hole is bordered by the Hoback normal fault with uplift to the east, opposite to that along the Teton fault. The Hoback fault has a total displacement of 3000 m, with 15 m of measured displacement on post-15,000-yr old loess (Love *et al.*, 1973). Gilbert and Piety (written communication, 1983) have estimated a post-loess displacement of 10 m for the Hoback fault based on a single scarp profile. Displacements along the Teton and Hoback faults appear to die out as they converge on the east-west trending Cache Creek thrust near Jackson, a major fault formed during the Laramide orogeny that may have been active as late as Pliocene time (Love *et al.*, 1973). The interactions between these two normal faults and the older thrust structure are not understood. The Hoback fault continues southward as part of a series of *en echelon* normal faults of the Intermountain seismic belt.

The southwestern end of Jackson Hole is bordered by the Snake River Range, a range composed of a series of imbricate thrust sheets emplaced in early Eocene time (Love *et al.*, 1973) and bounded on its western side by the Grand Valley normal fault. This range appears to have been formed at the same time as the Hoback Range, a range of similar thrust sheets located east of the Hoback fault.

The central portion of Jackson Hole is cut by several small faults (Figure 1) with Quaternary displacements (Table 1). Flat Creek valley, north of Jackson, has been downdropped by a fault that has 61 m of post-15,000-y-old loess displacement (Love and Taylor, 1962). However, there is no evidence for a major bounding fault between Jackson Hole and the Gros Ventre Range.

Little evidence for Quaternary fault displacement is known for the Gros Ventre Range and Mount Leidy Highlands, areas extensively deformed by Laramide thrust structures (Love *et al.*, 1973). Numerous large landslides have occurred in the Gros Ventre Range and the 1923 Gros Ventre landslide may have been related to earthquake swarm activity (Smith *et al.*, 1976).

TABLE 1

FAULT DISPLACEMENT, FAULT LENGTH, AND AGE ESTIMATES FOR FAULTS IN THE TETON REGION

Fault or Fault Segment	Age of Displaced Unit (yr)	Length (km)	Displacement (m)	Map No.*	Reference No.†
Wilson	>20,000?	23.0	?	1	5
Teton Village	11–14,000	9.0	8.2	2	1
Granite Creek	11–14,000	6.0	11.3	3	1
Granite Canyon	11–14,000	10.5	4.6	4	1
South Taggart	11–14,000	5.0	11.3	5	1
Taggart Lake	11–14,000	5.0	12.2	6	1
Avalanche Canyon	11–14,000	10.0	5.2	7	1
Lupine Meadow	11–14,000	3.5	10.7	8	1
String Lake	11–14,000	5.5	19.2	9	1
Bearpaw Bay	11–14,000	7.5	23.8	10	1
North Teton	<1,900,000	17.0	2130.0	11	1
Beulah Lake	6–700,000	17.0	200.0	12	2
Mt. Sheridan	<1,900,000	32.0	300.0	13	2
Bobcat Ridge	<1,900,000	27.0	300.0	14	2
Huckleberry Mountain	<1,900,000	21.0	400.0	15	2
Hoback	12–15,000	56.0	15.2	16	3
Tetonia	<1,900,000	21.0	122.0	17	3
Hermitage Point	<1,900,000	40.0	451–1067	19	1
E. Gros Ventre Butte	<12,000	19.0	46.0	20	4

* Map numbers refer to fault segments in Figure 1.

†1, Gilbert *et al.* (1982); 2, Witkind (1975), J. D. Love (oral communication, 1980); 3, Love *et al.* (1973); 4, Love and Taylor (1962); 5, this segment was assigned a slip rate of 0.03 cm/yr, the minimum rate observed along the Teton fault.

The western side of the Teton Range is partly bounded by a series of small faults. Most of these faults are between 10 and 20 km in length, as compared to the 70-km length of the Teton fault. Quaternary displacements along these faults, however, are significant. Love *et al.* (1973) have measured up to 120 m of displacement of ash flow sheets on several faults near Tetonia, Idaho, although recent alluvial fans that cross these faults do not appear to be displaced. It is not clear whether these faults are directly related to major uplift of the Teton Range, since little is known about their subsurface configuration.

North of Jackson Hole, a series of *en echelon* faults extends northward to Yellowstone Lake and displaces Quaternary rhyolite flows of the Yellowstone Plateau. These faults displace the 1.9 m.y. old Huckleberry Ridge tuff by up to 400 m (J. D. Love, oral communication, 1980). Due to the area's thick vegetation and remoteness, it is difficult to determine the age of the most recent movements along these faults.

The Teton fault branches into two segments near the northern end of Jackson Lake and the western segment appears to die out under the 70,000-yr-old Pitchstone Plateau rhyolite flows (Christiansen and Blank, 1972). The eastern segment merges into the remains of a ring-fracture system formed during the collapse of Yellowstone's first caldera cycle 1.9 m.y. ago (Christiansen and Blank, 1972).

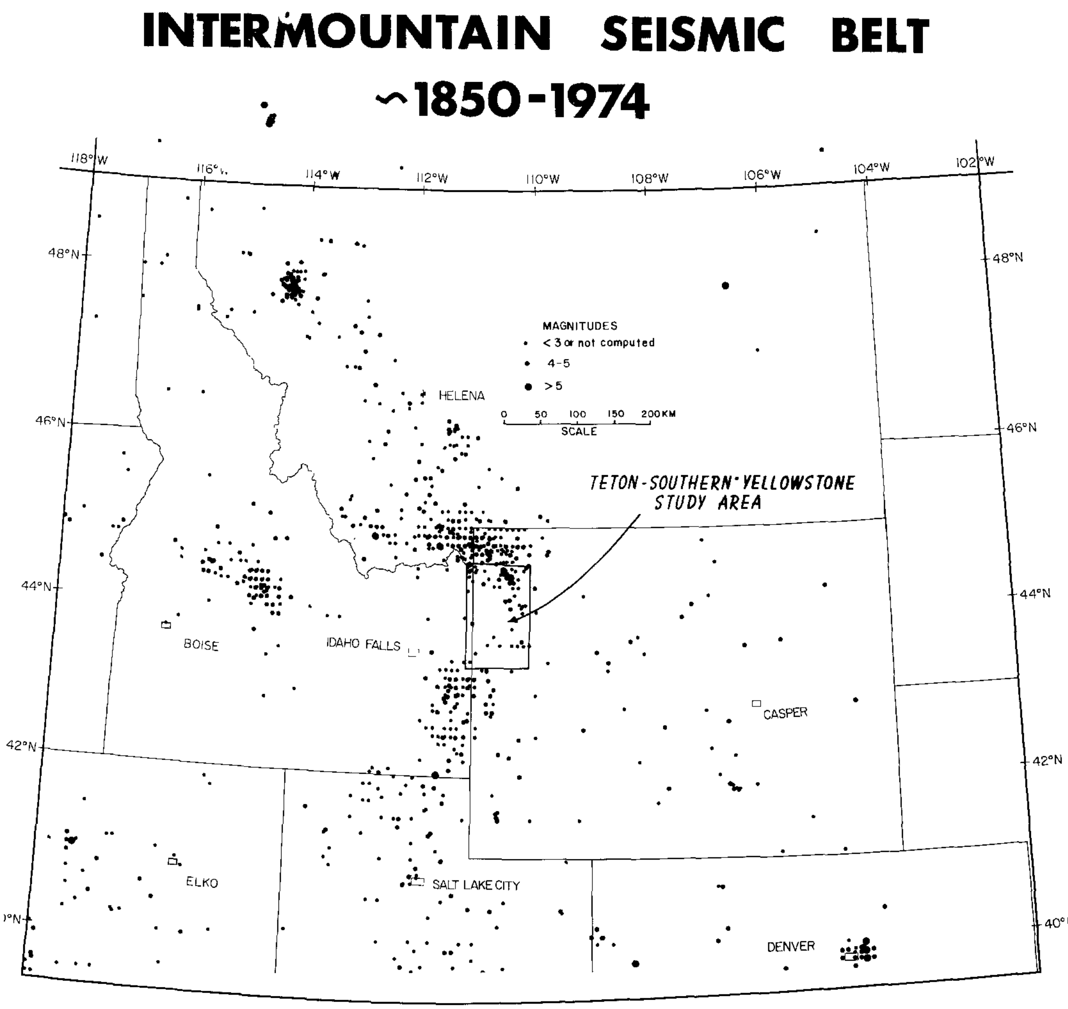


FIG. 2. Location of the Teton study area with respect to the Intermountain seismic belt.

HISTORIC AND INSTRUMENTAL SEISMICITY

The Teton-southern Yellowstone seismicity forms part of the southern Intermountain seismic belt that links the seismicity of the Yellowstone Plateau-Hebgen Lake system to the north with a northeast-trending zone of seismicity along the Wyoming-Idaho border to the south (Figure 2). Although large earthquakes have not occurred in the Teton region during historic times, one $M = 7.1$ and six $M \geqq 6.0$ earthquakes have occurred in the Hebgen Lake-Yellowstone Plateau region. Displacements of late Quaternary deposits indicate that similar size prehistoric earthquakes may have occurred along the Teton fault (Gilbert *et al.*, 1982).

Although small earthquakes have been felt in the Teton-Jackson Hole region, no earthquake has exceeded an intensity of VI on the modified Mercalli scale (Coffman and von Hake, 1973). Earthquakes felt in the region between 1923 and 1975 are discussed by Smith *et al.* (1976). From 1923 to 1975, felt earthquakes occurred primarily in the central Gros Ventre Range, southern Jackson Hole and Driggs, Idaho regions. Historical accounts of these earthquakes do not suggest that the earthquakes occurred along the Teton Fault zone (Smith *et al.*, 1976). In March 1977, a sequence of felt earthquakes occurred on the western edge of the Teton Range near Driggs, Idaho, the largest event with $M_L = 2.6$ (Bones, 1978). The University of Utah Seismograph Stations has recorded two sequences of small earthquakes, with the largest event of $M_L < 4.0$, that were felt throughout the Jackson Hole area. The first sequence occurred beneath the southern end of Jackson Hole in 1979, and the second sequence occurred east of the town of Jackson near Cache Creek Canyon during the spring and summer of 1981. None of the post-1975 felt earthquakes were located near the Teton fault zone.

Earthquake activity in the southwestern Yellowstone Plateau primarily occurs in swarms. Information on felt activity in this area is limited due to its remoteness from areas of permanent human settlement, although a large swarm of felt events located in the Pitchstone Plateau region was recorded during February and March of 1981 (A. M. Pitt, U.S. Geological Survey, oral communication, 1981).

From 1950 to the early 1970s instrumental monitoring of Teton-Jackson Hole seismicity was limited to earthquakes with $M_L \geqq 3.0$ recorded by the U.S. Coast and Geodetic Survey (USCGS) network with an estimated location accuracy of ± 20 km. Earthquake activity in the central and northern Yellowstone Plateau was monitored from the early 1970s to November 1981 by the U.S. Geological Survey (USGS) seismic network. Seismicity in the eastern Snake River Plain and southeastern Idaho region has been monitored by seismic networks operated by the Idaho National Engineering Laboratory (INEL), the USGS, the University of Utah and Ricks College, beginning in 1971. Data from these networks were brought into a single recording laboratory at the University of Utah in 1978. Due to poor azimuthal coverage with the closest stations located 50 to 60 km from the Teton-Jackson Hole region, the University of Utah Seismograph Stations epicenter locations have an accuracy of about ± 15 km.

Prior to 1979, studies of small ($M_L < 3.0$) local earthquakes occurring in the Teton area were limited to microearthquake surveys in the southwest corner of Jackson Hole in 1977 (Bones, 1978) and the Mount Leidy Highlands-Gros Ventre area in 1975 (Smith *et al.*, 1976). A 2-week survey in 1974 focused on the Jackson Lake area (Smith *et al.*, 1976), but yielded little information. Microearthquake surveys in the Yellowstone-Hebgen Lake region have been operated since 1971, but none have focused on the southwestern Yellowstone Plateau. In the summer of 1979, a five-station array was operated for 3 months around the Jackson Lake dam by the Bureau of Reclamation. This effort represented the longest term study of seismicity in the region, but only gave information on the central Teton fault-Jackson Lake area. In 1980, we began a 2-yr program to monitor the seismicity throughout the region that forms the primary source of data for this paper.

Our 1980 study focused on the seismicity of the northern part of the area (Figure 3). Earthquake activity was monitored from 1 August to 22 September 1980 using nine portable smoked-paper recorders, supplemented by permanent stations of the USGS Yellowstone network and three stations in Idaho and Wyoming operated by Ricks College (Figure 3). Three of the portable instruments reoccupied sites used

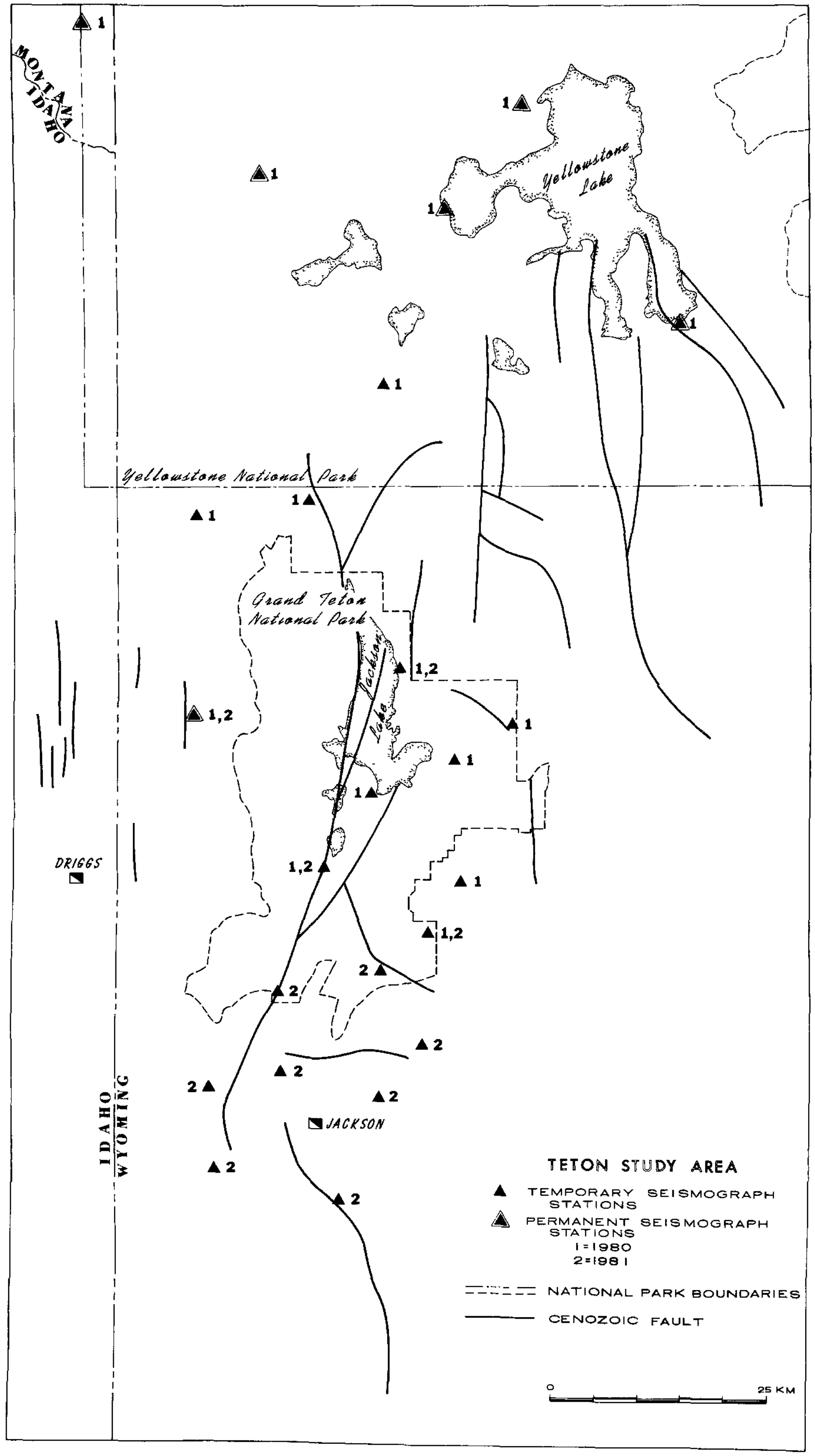


FIG. 3. Location of seismograph stations used in the 1980 and 1981 seismicity surveys.

in the 1979 Bureau of Reclamation survey, enabling us to relocate 1980 and 1979 events jointly.

Our 1981 survey focused on the central and southern Teton region. The survey, conducted from 3 August to 13 September 1981, employed 11 portable recorders, supplemented by additional permanent University of Utah and Ricks College stations (Figure 3). Several station sites used in 1980 were reoccupied during this survey.

TETON SEISMICITY (1973 TO 1981)

Epicenters of earthquakes recorded during the 1980 and 1981 surveys are shown in Figure 4. Locations were obtained using a modified version of HYPO71 (Lee and Lahr, 1975). One-dimensional velocity models used in the location process were based on interpretations of seismic refraction lines (Table 2) by Schilly (1979), Schilly *et al.* (1982), and Tibbetts *et al.* (1969). Epicenters shown in Figure 4 met the following standards: (1) the epicenter rms location error (Lee and Lahr, 1975) was less than 0.2 sec. (2) The closest station to each earthquake was at most 20 km away. (3) Epicenter locations used readings from a minimum of four stations, hypocenter locations a minimum of five stations. (4) Hypocenter locations had an azimuthal gap in station distribution of less than 200°. Use of these standards eliminated some earthquakes from consideration that were located outside the network. Estimates of location accuracy for earthquakes within the network are ± 0.6 km in epicenter coordinates and ± 1.0 km in focal depth.

Seismicity monitored in the northern part of this region in 1980 occurred primarily in the central Pitchstone Plateau south of Shoshone Lake and near the southern entrance to Yellowstone National Park. Earthquake activity in the Pitchstone Plateau area did not appear to be associated with known Quaternary faulting and focal depths of these earthquakes were in the 3 to 9 km range. During February and March of 1981, the USGS Yellowstone network recorded a swarm occurring in the same region with several events in the $2.0 \leqq M_L \leqq 3.0$ range (A. M. Pitt, USGS, oral communication, 1981). Activity near the southern entrance to Yellowstone National Park may have been associated with the northeastern portion of the Teton fault zone with focal depths from 7 to 10 km.

In 1981, seismicity monitored in the southern area of the region was higher than had been previously noted. A significant sequence of events occurred near the southern Teton National Park boundary along the Teton fault zone. The earthquakes occurred along two trends, one striking north-south and parallel to the trace of the Teton fault and the other striking east-west, nearly perpendicular to the fault. Focal depths for the earthquakes ranged between 4 and 8 km with the majority occurring between 4 and 6 km. Another sequence of earthquakes occurred in the Teton Pass region west of Wilson. An inferred splay of the Teton fault, the Phillips Canyon fault, has been mapped by Love and Reed (1975) 1 to 2 km south of the area of earthquakes near Teton Pass. A third area of concentrated earthquake activity was located in the Mosquito Creek region at the southern end of the Teton fault. Focal depths for both the Teton Pass and Mosquito Creek events ranged from 6 to 8 km. It should be noted that during the 1981 survey, seismic reflection crews were operating in both the Teton Pass and Mosquito Creek regions, and blasting was taking place near Teton Village. As a result, events recorded in these regions were carefully scrutinized to avoid the inclusion of any man-made seismic events.

During both 1980 and 1981 a diffuse pattern of epicenters was observed in the Gros Ventre and Mount Leidy Highlands regions. This pattern was similar to that observed by Smith *et al.* (1976) and could not be correlated with any surficial faults.

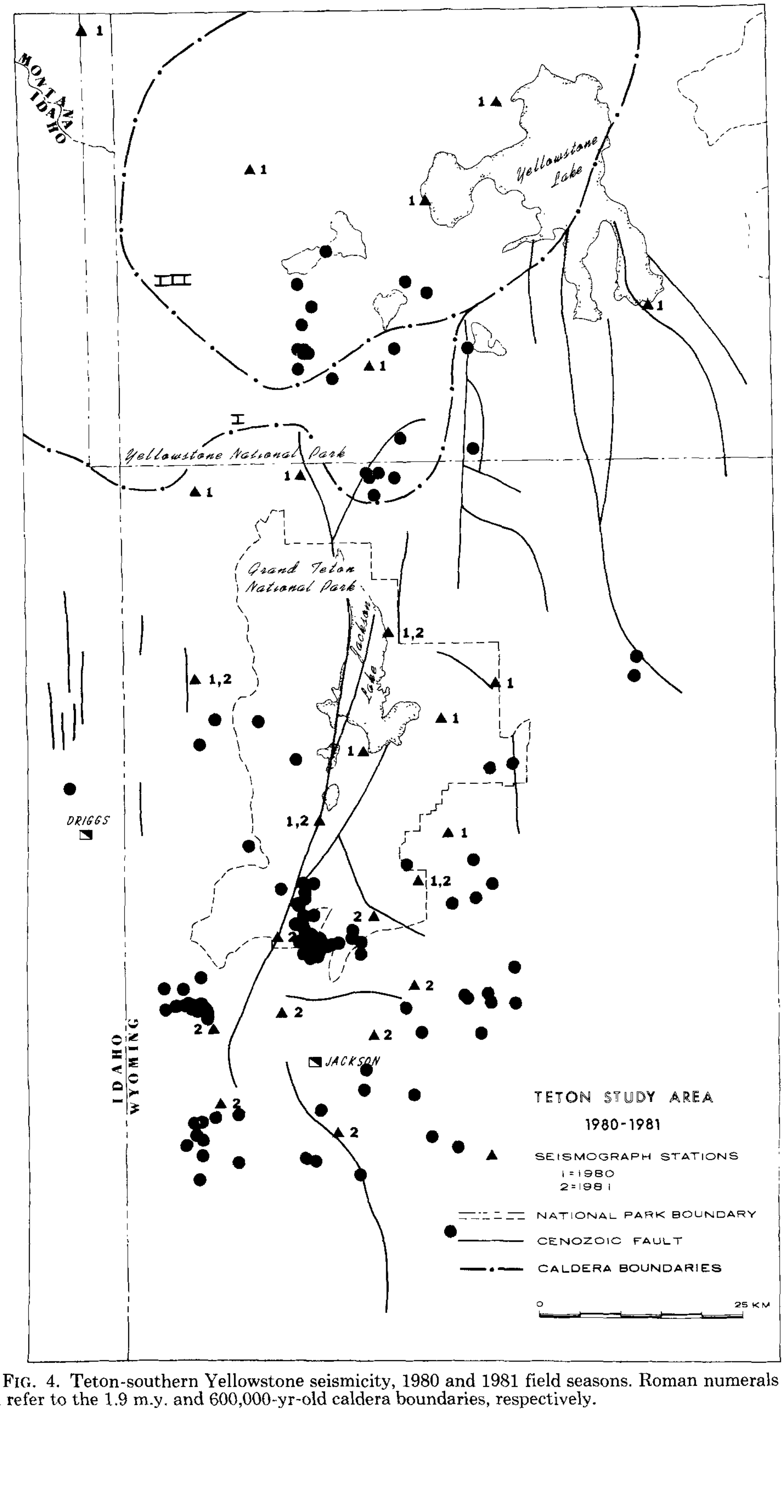


FIG. 4. Teton-southern Yellowstone seismicity, 1980 and 1981 field seasons. Roman numerals I and III refer to the 1.9 m.y. and 600,000-yr-old caldera boundaries, respectively.

A striking feature of all of the surveys discussed was the lack of earthquake activity along the north-central portion of the Teton fault extending along the western shore of Jackson Lake through Bearpaw Bay and southward about 20 km, despite the good instrumental coverage. A similar quiescence along this portion of the fault was noted by Smith *et al.* (1976), who had monitored the central fault zone for four weeks during 1974 and 1975. The southern part of the Teton fault from Wilson to its termination south of Mosquito Creek also appeared quiescent during 1981. Gilbert *et al.* (1982) have found no evidence of scarps along this portion of the fault zone, indicating that either there has been no postglacial movement along this segment or that the scarps have been eroded away by the Snake River and its tributaries. The north-central quiescent portion of the fault zone, however, has postglacial displacements of up to 24 m (Gilbert *et al.*, 1982), suggesting that this portion of the fault has been active in Holocene time. There are several possible explanations for the quiescence presently observed along this north-central portion of the fault: (1) the portion is locked and is storing strain energy. (2) The portion was active earlier in the Holocene but is now inactive, with segments to the immediate south near Teton Village now being active. (3) The portion is slipping aseismically. (4) The portion is episodically active at the microseismic level and microearthquakes, by chance, were not detected during the relatively short monitoring period.

TABLE 2

CRUSTAL VELOCITY MODELS FOR THE TETON REGION

Area	*P*-Wave Velocity (km/sec)	Depth* (km)
Jackson Hole-Gros Ventre Range		
	3.8	0.0
	4.9	1.1
	6.0	2.0
	6.8	17.5
Teton Range, west of the Teton fault		
	4.9	0.0
	6.0	0.5
	6.8	17.5
Eastern Snake River Plain		
	3.0	0.0
	4.9	1.5
	6.2	5.9
	6.6	11.8
	7.9	37.0
Southern Yellowstone Plateau		
	4.9	0.0
	6.0	4.5
	6.8	14.0

* Depth to top of horizontal layer, measured with respect to datum 2.0 km above sea level.

Earthquakes recorded during the 1980 and 1981 field surveys showed little correlation with the locations of felt earthquakes that occurred in south central

Jackson Hole in 1979 and east of Jackson in 1981. Since the felt events could be mislocated by 10 to 15 km, it is possible that the 1979 felt activity may have been associated with the observed 1981 activity in the Mosquito Creek region. However, there appeared to be no major activity east of Jackson that could be related to the felt events occurring there earlier in 1981.

In an effort to refine the spatial resolution of the seismicity of the Teton region, local and regional earthquakes from 1973 to 1979 were relocated using the same velocity models and location criteria as for the 1980 to 1981 study. A map of these epicenters and epicenters from the 1980 to 1981 study is shown in Figure 5. The combined information (Figure 5) points out the same trends seen in the 1980 to 1981 data. First, seismicity in the Gros Ventre-Mount Leidy region was diffuse and unrelated to any observable surface structures in the region. Locations of earthquakes recorded during Bones' (1978) southeastern Idaho-Wyoming border survey correlated well with the earthquake activity observed in the southern Jackson Hole-Mosquito Creek area in 1981.

The general pattern that emerges from the epicenter map (Figure 5) is that the Teton-Jackson seismicity is part of a zone that continues southwestward into southeastern Idaho forming a major component of the Intermountain seismic belt (Figure 2). Earthquake activity along the western part of the Teton range is also apparent, and some of the seismicity appears to be associated with the Tetonia fault system. In Yellowstone, the activity is generally diffuse with some activity associated with faults on the western side of Yellowstone Lake.

In a further effort to discriminate spatial trends, earthquakes with sufficient information for good hypocenter determination were relocated using the joint hypocenter program FASTJHD (Herrmann *et al.*, 1981). Due to the large size of the study area and the variability of the velocity models, relocations were done for smaller clusters of earthquakes, rather than the entire region (Figure 6).

A cross section of hypocenters (Figure 7) shows that earthquakes in the northern Snake River and southern Teton Ranges have a range in focal depths of 4 to 8 km. In the Gros Ventre area, however, earthquakes occur at greater depths of 8 to 10 km with some in the 20 to 25 km depth range. Several earthquakes beneath the Gros Ventre Range that did not meet the hypocenter location criteria also appeared to be in this depth range. Information on focal depths in the northern Teton-southern Yellowstone region was limited, but it does not appear that earthquakes occur at significantly shallower depths than 4 to 8 km beneath the southern boundary of the 600,000-yr-old Yellowstone caldera. Earthquakes do appear to occur at shallower depths as one approaches the western boundary of this caldera from Hebgen Lake (Smith *et al.*, 1977).

Fault Plane Solutions

Composite fault plane solutions obtained from microearthquakes are shown in Figures 8 and 9. Solutions for the Yellowstone Lake (A) and Mount Leidy (B) regions were taken from Smith *et al.* (1977), the remaining solutions were obtained from the 1980 and 1981 surveys. In the case where several solutions appeared to fit the first motion data, $(SV/P)_z$ amplitude ratios (Kisslinger *et al.*, 1981) were used to resolve which solution fit the amplitude data better.

Fault plane solutions for the southern Teton area (C, D, and E) show normal faulting along faults trending in a north-south direction consistent with the strike of the eastward-dipping Teton fault. If these solutions correspond to earthquakes on the Teton fault, then one set of nodal planes would indicate that the fault dips

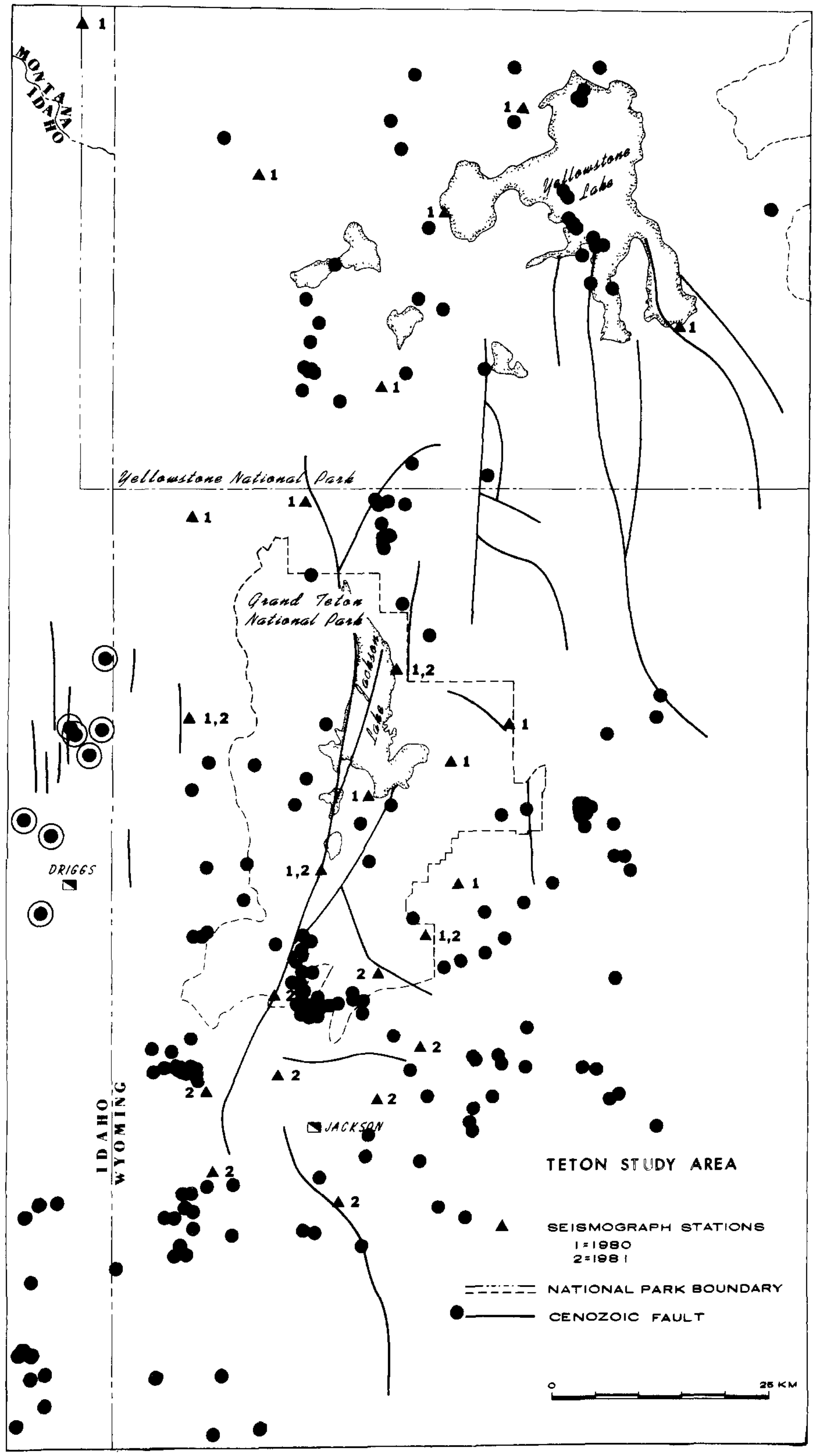


FIG. 5. Local and regional seismicity of the Teton-southern Yellowstone area 1973 to 1981. Epicenters of earthquakes recorded at regional distances are indicated by circled dots and are relocations of Bones' (1978) epicenters. Epicenters from local earthquakes include epicenters from this study as well as relocated epicenters from microearthquake surveys by Smith *et al.* (1974, 1976), Bones (1978), and the Bureau of Reclamation (1980, J. Michaels, written communication)

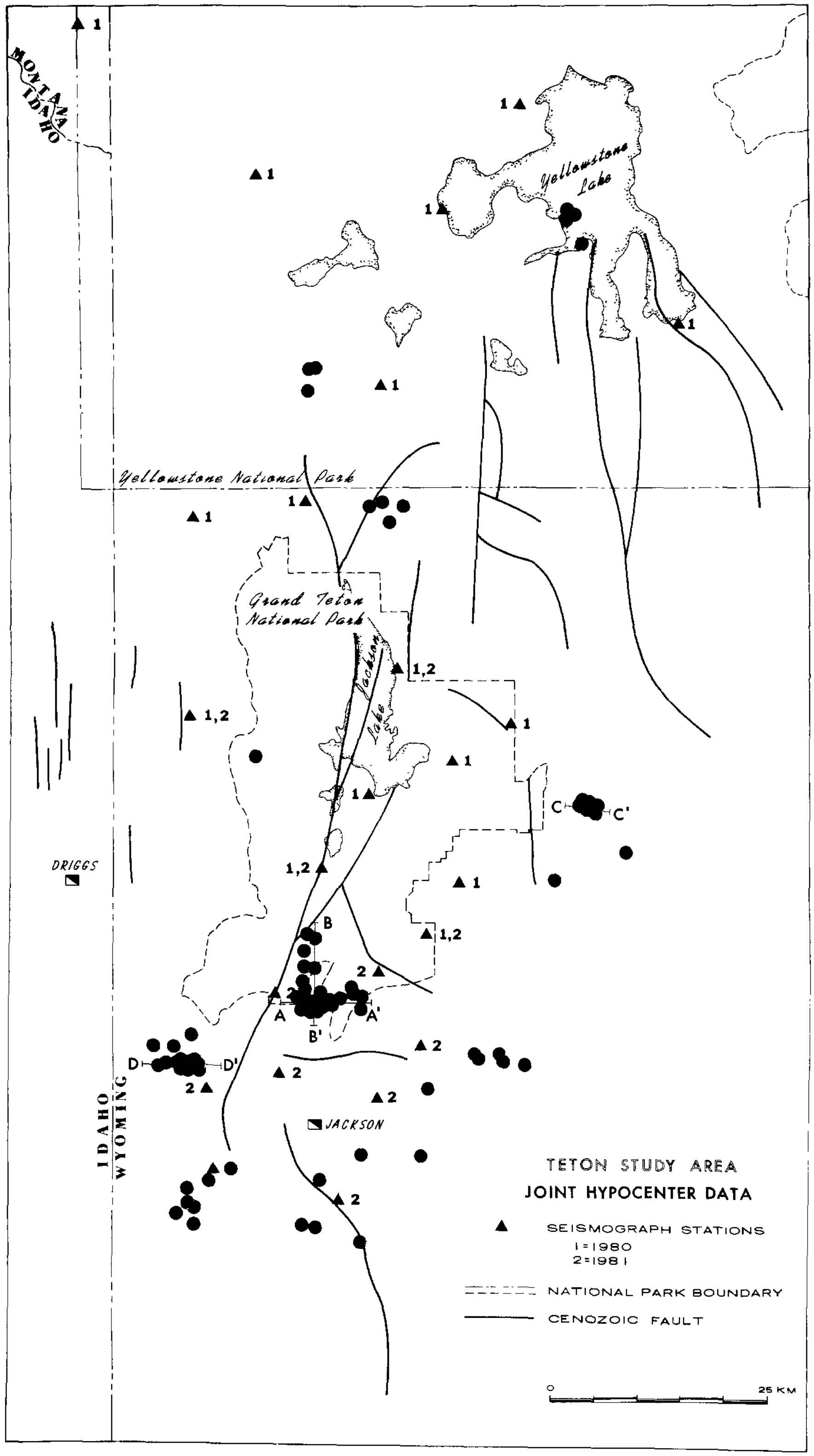


FIG. 6. Epicenters of relocated earthquakes from 1973 to 1981. Cross section lines *A-A′*, *B-B′*, *C-C′*, and *D-D′* refer to Figures 10 to 12.

eastward at 30° to 50°. In an east-west cross section across the Teton fault (Figure 10), a comparison can be made between focal depths and hypothetical projections of dip on the Teton fault with depth (see Figure 6 for the location of all cross section lines). The solid line represents a 60° dip on the fault, and the dashed lines bracket a range of dips (35° to 45°) interpreted from gravity models by Tibbetts *et al.* (1969). The hypocenters indicate a range in dip of 45° to 60° to the east if these foci are associated with the Teton fault. An east-west trend of epicenters in the area suggests a fault striking in an east-west direction, but a north-south cross section of hypocenters (*B-B'*, Figure 10) across the area does not indicate that the observed

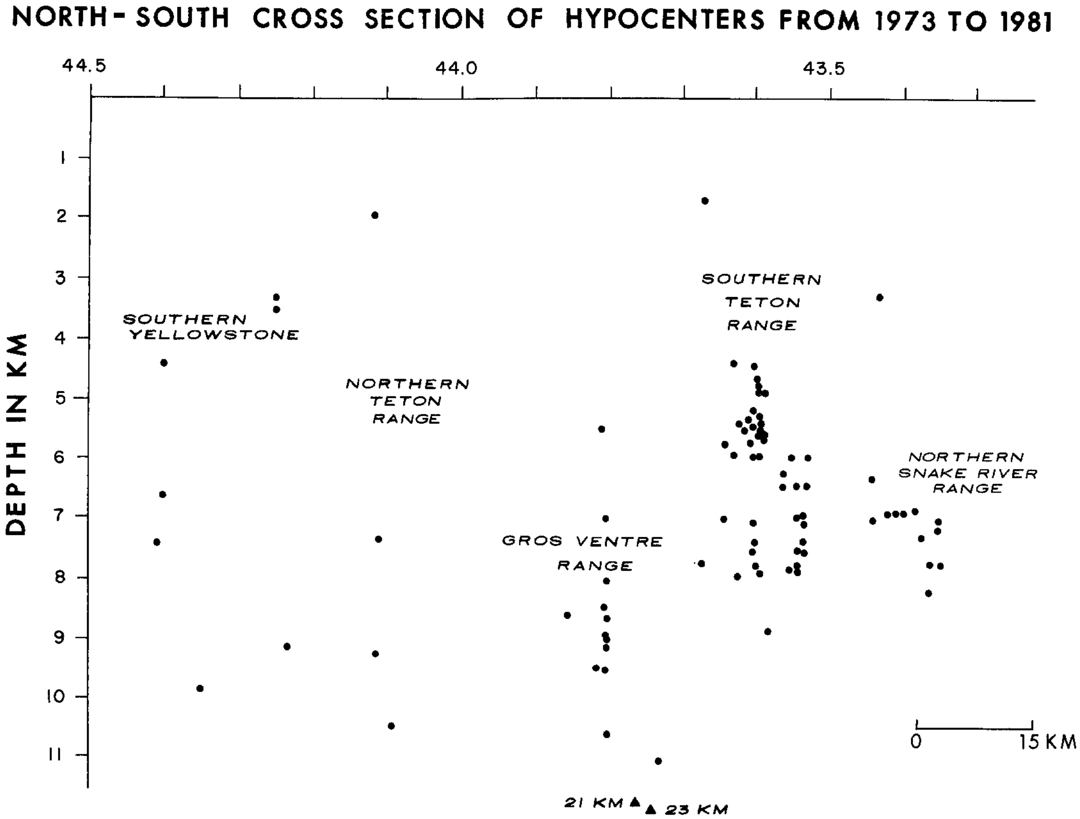


FIG. 7. North-south cross section of earthquakes shown in Figure 6. Vertical exaggeration is 7.6.

seismic activity is occurring along a well-defined fault dipping to the north or south. The strike of nodal planes for solution (E), a composite solution of earthquakes occurring in the east-west trend, also is not consistent with an east-west trending fault.

The fault plane solution for the Mount Leidy Highlands region (B) indicates extension in a northwest-southeast direction on a normal fault. Since there is no evidence of Quaternary faulting in the region, one cannot differentiate the actual fault plane from the auxiliary plane based on surficial geology.

A seismic reflection profile of the Mount Leidy Highlands area (Figure 11) has been released to us by the Clayton Williams Oil Company. This profile crossed directly over the area of earthquake activity. An interpretation of the unmigrated reflection profile is shown with a cross section of microearthquake foci (Figure 11). The reflection line shows a subsurface fault on the flank of an anticlinal structure

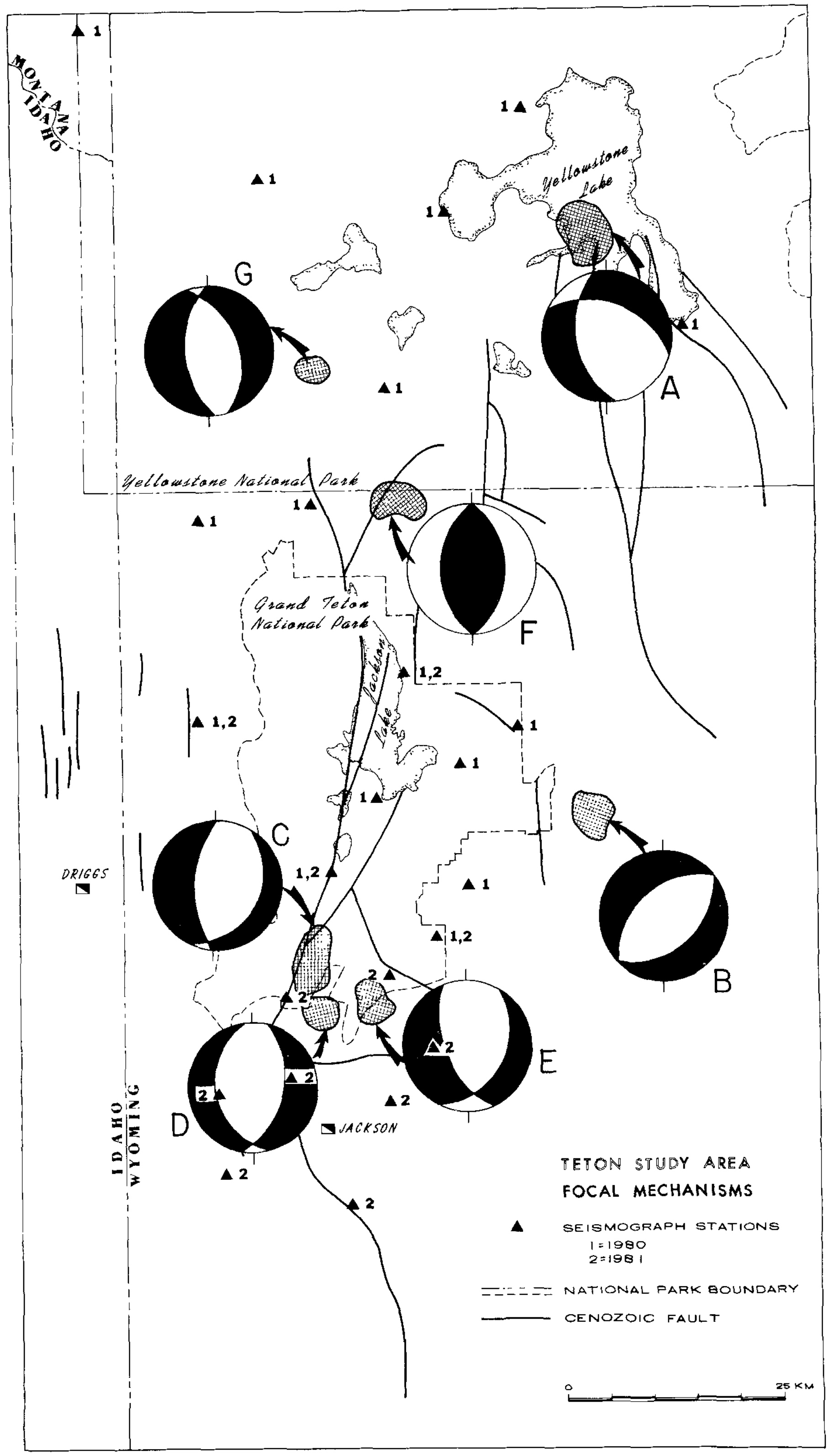


FIG. 8. Composite fault plane solutions from microearthquakes in the Teton-southern Yellowstone region. Focal mechanisms shown are lower hemisphere projections. White areas indicate dilatation, black areas indicate compression. Stippled areas show locations of earthquakes used in composite solution. Solutions A and B are from Smith *et al.* (1977).

that offsets the Precambrian basement and lowest sedimentary strata. Offset of the basement along the fault is estimated to be about 400 m. The fault has a reverse sense of motion and dips at a high angle to the east. Such a fault may have been formed during the thrusting event that formed the nearby Spread Creek anticline in early Paleocene time (Love *et al.*, 1973). Present day seismicity, in this case, may represent the reactivation of an older fault with movement in the normal sense along the eastward-dipping fault plane indicated by the composite mechanism. There also appears to be some association between seismicity in other parts of the Gros Ventre-Mount Leidy region and older basement structures that have been

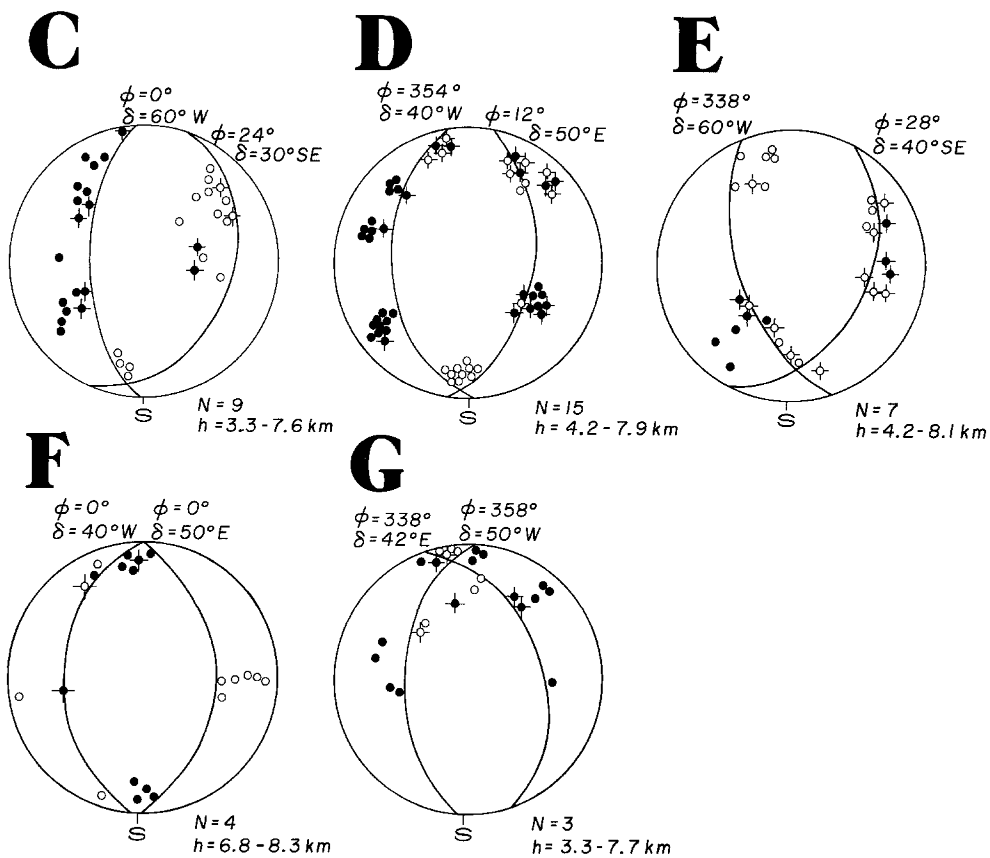
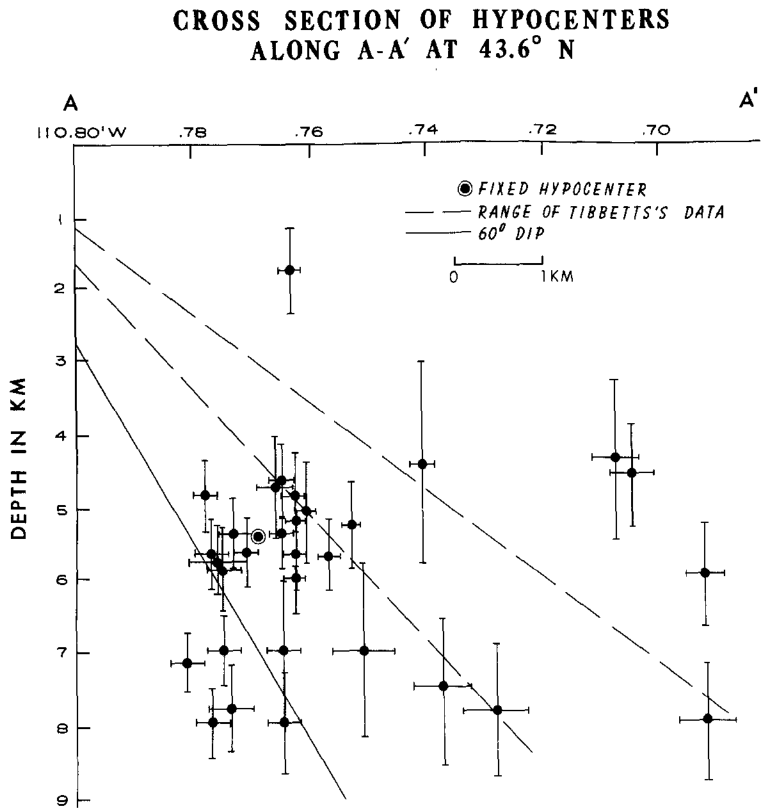


FIG. 9. Composite fault plane solutions determined from 1980 and 1981 field data. Open circles indicate dilatation, dark circles indicate compression. Circles with crosses indicate near-nodal first motions. The strike and dip of the fault planes are φ and δ, h is the depth range of the earthquakes used in the solution, and N is the number of earthquakes used in the solution. $(SV/P)_z$ ratios were used to help constrain the nodal planes for solutions D and E.

interpreted from seismic reflection lines that cross these areas. Focal depth control in the areas is poor, and hence we are not able to determine whether this seismicity also represents possible reactivation of older reverse and thrust faults.

The composite focal mechanism for the southern Yellowstone Park area (F) represents the only mechanism with reverse motion observed in the entire Teton region. The southern Yellowstone Park area has a complex history of *en echelon* normal faulting along branches of the Teton fault and along the circular ring-fracture system of the 1.9 m.y. old Yellowstone caldera. Complicated interaction between these obliquely converging faults might produce a localized compressional stress regime.



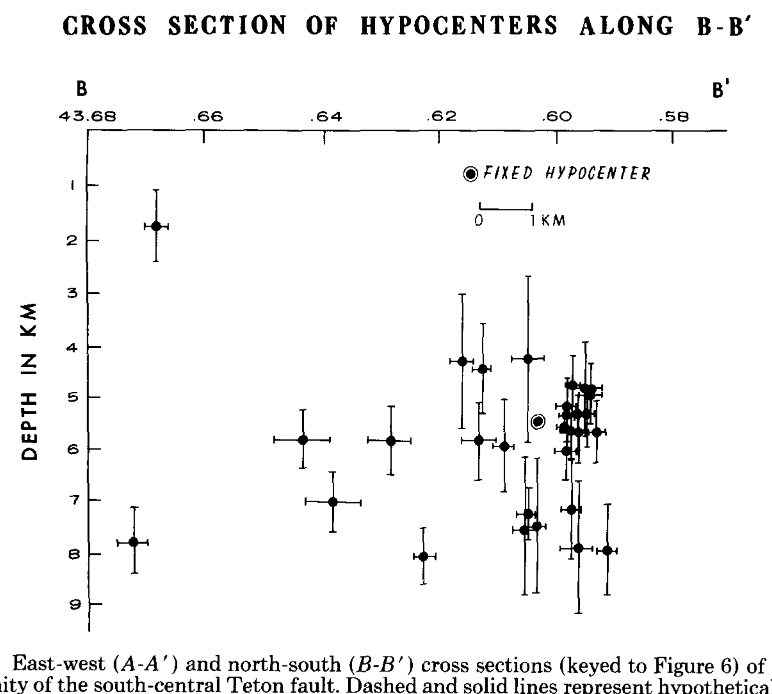


FIG. 10. East-west (*A-A′*) and north-south (*B-B′*) cross sections (keyed to Figure 6) of hypocenters in the vicinity of the south-central Teton fault. Dashed and solid lines represent hypothetical projections of the Teton fault extrapolated from its surface trace. There is no vertical exaggeration in either cross section. The master event is denoted by the circled dot.

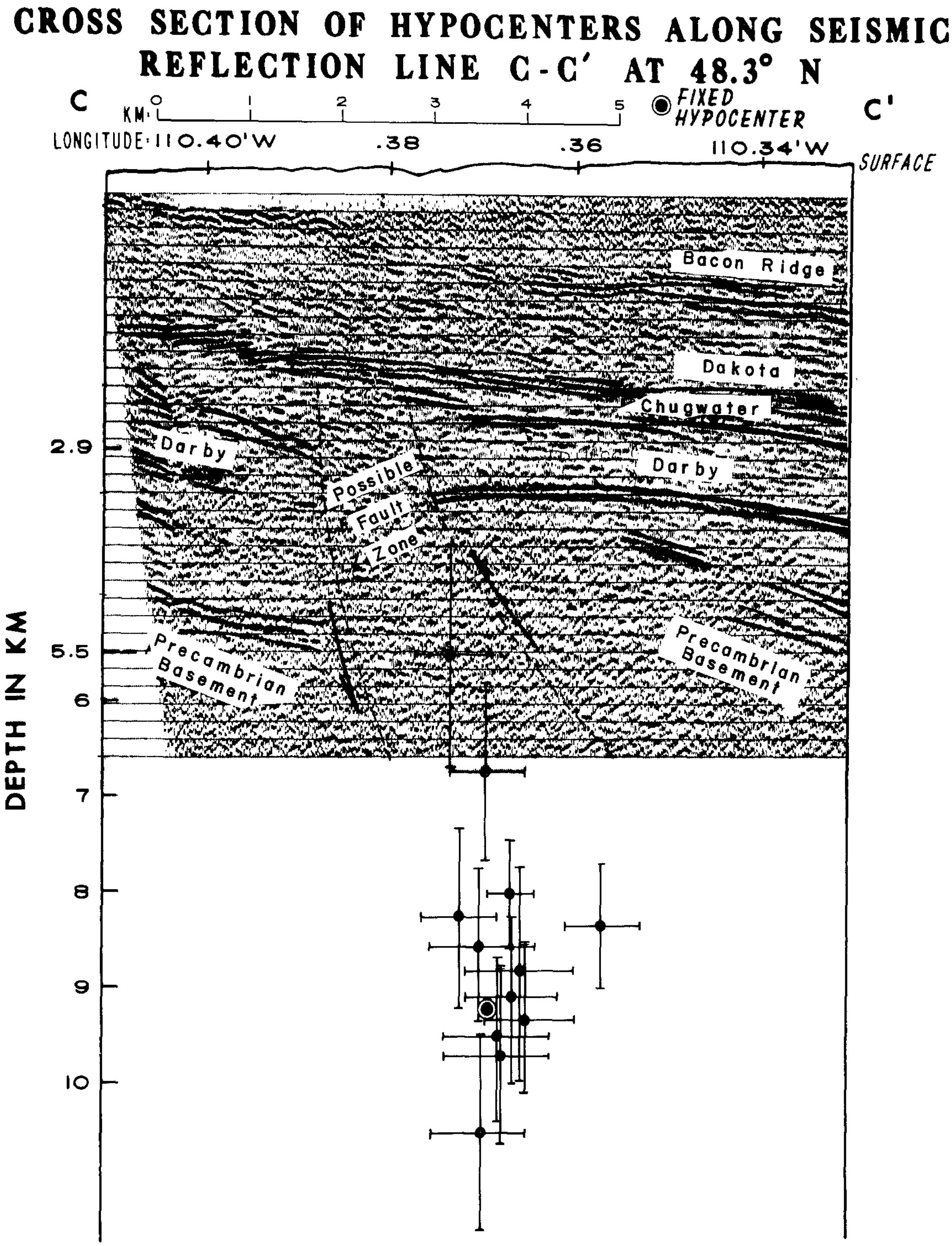


FIG. 11. Cross section (*C-C′*) of hypocenters in the Mount Leidy Highlands region along a simplified interpretation of a seismic reflection line. Since the line has not been migrated, the *upper part* of the figure does not have a linear depth scale. Depths to several stratigraphic horizons are noted on the *left*. The depth scale below the top of the western block of Precambrian basement is linear. The vertical exaggeration in the *lower half* of the figure is 0.5. The master event is denoted by the circled dot. (See Figure 6 for cross-section location.)

In the Pitchstone Plateau region (G), faulting is consistent with that observed farther to the south along the Teton fault, suggesting that continuity in the stress field exists between the southern Tetons and the southern Yellowstone Plateau. Near Yellowstone Lake, the focal mechanism (A) indicates extension in a northeast-southwest direction along a normal fault. The strikes of both nodal planes are consistent with the trends of mapped Quaternary faults. It is interesting to note that within 60 km to the northwest of the Pitchstone Plateau and Yellowstone Lake

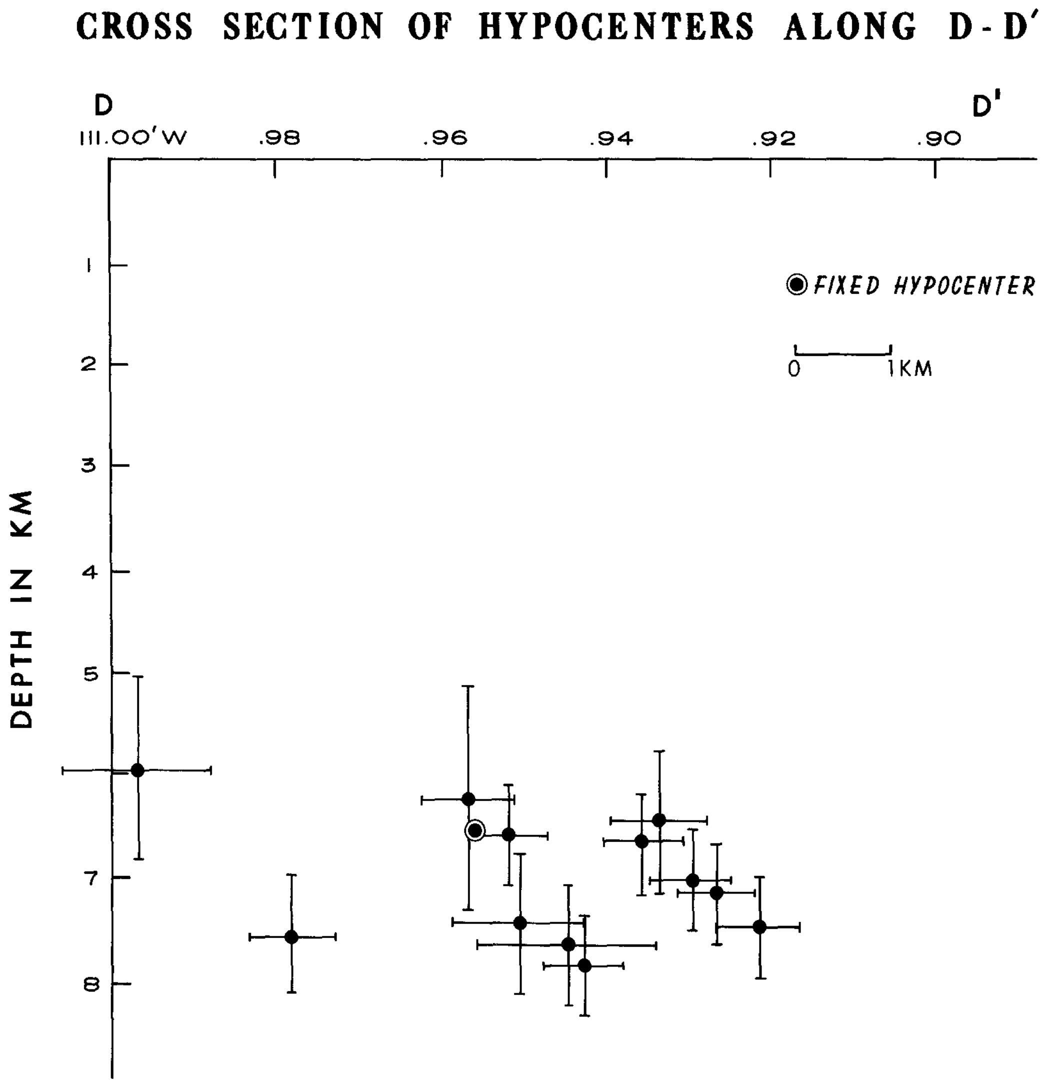


FIG. 12. Cross section (D-D') of hypocenters in the Teton Pass region. There is no vertical exaggeration. The master event is denoted by the circled dot. (See Figure 6 for cross section location.)

area, the focal mechanisms associated with Hebgen Lake fault zone seismicity show general north-south extension (Smith *et al.*, 1977). This implies that the least compressive stress direction rotates by 90° across the Yellowstone region, a feature earlier noted by Smith *et al.* (1977).

Azimuthal coverage was insufficient to obtain focal mechanisms for earthquakes in the Mosquito Creek and Teton Pass areas. An east-west cross section of focal depth through the Teton Pass region (Figure 12) shows little indication of dip. A north-south cross section (not shown) through the same data also reveals no trend in hypocenters that could be associated with the inferred trace of the Phillips Canyon fault.

Seismic Moment Rates and Return Periods

Due to the limited record of instrumental seismicity available for the Teton region, earthquake frequency-magnitude relationships could not be confidently estimated. However, using information from recent mapping of Quaternary faults by Gilbert *et al.* (1982) and Love *et al.* (1973), estimates of geologic moment rates were obtained for several fault zones. Because major faults in the region generally trend north-south, we assumed they were subject to a uniform stress field. This

TABLE 3

Geologic Moment Rates for Faults in the Teton Region

Fault or Fault Segment	Maximum Depth of Faulting (km)	Geologic Moment Rate ($\times 10^{22}$ dyne-cm/yr)
Wilson	10.0	2.6
Teton Village	10.0	2.3
Granite Creek	10.0	2.1
Granite Canyon	10.0	1.5
South Taggart	10.0	1.7
Taggart Lake	10.0	1.9
Avalanche Canyon	10.0	1.6
Lupine Meadow	10.0	1.1
String Lake	10.0	3.2
Bearpaw Bay	10.0	5.4
North Teton	12.0	8.7
Beulah Lake	12.0	2.4
Mt. Sheridan	12.0	2.3
Bobcat Ridge	12.0	2.0
Huckleberry Mountain	12.0	2.0
Hoback	12.0	28.8
Tetonia	12.0	0.6
Hermitage Point	10.0	6.1
E. Gros Ventre Butte	12.0	33.3

assumption was used as the basis for application of the method of Brune (1968) to determine regional moment rates $\dot{M}_0$, where

$$\dot{M}_0 = \mu A s. \tag{1}$$

μ is the shear modulus (3.3×10^{11} dyne/cm^2), A the fault area, and s the slip rate along the fault. Maximum depths of faulting for each fault were based on the maximum depths of earthquakes occurring near the fault and are listed in Table 3. Faults were assumed to dip at an angle of 60°. Fault length and fault slip information used to calculate moment rates are listed in Table 1. Moment rates for each fault are listed in Table 3. There may be as much as a factor of 2 error in these moment rate estimates. For example, if faults in the region actually dipped at 30°, the moment rates would increase by a factor of 1.7.

Estimates of moment rates were obtained for the Teton fault from several sources of geologic information. Using surface displacement and length estimates from Gilbert *et al.* (1982), and assuming a scarp age of 11,000 to 14,000 yr, we obtain an average moment rate of 3.5×10^{23} dyne-cm/yr for the 100-km length of the Teton fault. If the 2130 m displacement of the Huckleberry Ridge tuff is used, a moment rate of 4.5×10^{23} dyne-cm/yr is obtained. Therefore, an average moment rate for the fault would be 4.0×10^{23} dyne-cm/yr. If we consider only the part of the Teton fault that has experienced the latest surface rupture, a segment 56 km in length (Gilbert *et al.*, 1982), the moment rate is estimated to be 2.5×10^{23} dyne-cm/yr. Love and Montagne (1956) have measured displacements of 45 to 60 m in 20,000-yr-old sediments along this segment that would give an estimate of 5.6×10^{23} dyne-cm/yr for the moment rate along the segment. Using these moment rates, an average of 4.1×10^{23} dyne-cm/yr is obtained for the segment.

Geologic moment rates were also estimated for several faults in the Yellowstone Plateau and Jackson Hole areas (Table 3). A regional moment rate was obtained by summing these estimates with moment rates estimated for the Teton, Hoback, and Tetonia fault systems. The average geologic moment rate for the entire region was 1.1×10^{24} dyne-cm/yr.

To determine how these moment rates relate to the return periods of large earthquakes, we compared geologic moment rates with moment rates estimated from historic data of other regions of the Intermountain seismic belt. Both Molnar (1979) and Anderson (1979) have developed relationships for determining seismic moment rates from historic data. Anderson (1979) arrived at an expression for the moment rate by truncating the log–moment density function at some maximum moment, $M_0^{\max}$, whereas Molnar (1979) truncated the cumulative moment distribution at $M_0^{\max}$. Molnar's (1979) method produces a spike in the density function at $M_0^{\max}$. Hyndman and Weichert (1983) suggest that such a spike is not physically resonable, so we have chosen to use Anderson's (1979) expression. It is important to note that Anderson's (1979) method gives a return period of infinity for an earthquake with moment equal to $M_0^{\max}$. From Anderson (1979)

$$\dot{M}_0 = \frac{\alpha\beta(M_0^{\max(1-\beta)} - M_0^{\min(1-\beta)})}{1-\beta} \tag{2}$$

where $\beta = b/c$, $\alpha = \exp[\ln_e 10(a + db/c)]$, $M_0^{\max}$ is the maximum credible moment for the region, and $M_0^{\min}$ is the minimum moment required to produce surface breakage. The a and b values are from Gutenberg and Richter's frequency-magnitude relationship

$$\log N(M) = a - bM. \tag{3}$$

the c and d values from the moment versus magnitude relationship

$$\log M_0 = cM + d. \tag{4}$$

The historic and geologic moment rates were normalized to a map area of 1000 km^2 for comparison. The area used to normalize the Teton region extended from the Tetonia fault system east to the Bobcat Ridge fault, and from the northern end of the Mt. Sheridan fault to the southern end of the Hoback fault. The area used to normalize the moment rate for the Teton fault had a length of 100 km and a width of 6 km.

In our estimates of historic moment rates, we have used $c = 1.1$ and $d = 18.4$, values determined for Utah (Doser and Smith, 1982), because of the lack of reliable c and d values for many regions of the Intermountain seismic belt. Since seismicity and distribution of Quaternary faulting in Utah is similar to that of these regions, we feel that Utah values represent reasonable estimates. A maximum credible magnitude of $M_L = 7.5$ (Gilbert *et al.*, 1982) based on lengths of faulting and displacement relations was assumed for the Teton region. A moment corresponding to $M_L = 6.0$ was used as an estimate of the minimum moment required to produce surface breakage based on observations of earthquakes that have produced surface ruptures in the intermountain region.

If we consider geologic moment rates from the Teton area as representative of present day seismicity, a range of frequency-magnitude relationships that approximate Teton seismicity can be obtained from nearby regions that have historic moment rates similar to the Teton geologic rates. For example, the normalized geologic moment rate for the Tetons lies between the normalized historic moment rates for the Helena and Southwestern Montana regions (Table 4).

TABLE 4
HISTORIC AND GEOLOGIC MOMENT RATES

	Normalized Moment Rate (dyne-cm/yr/1000 km²)	Area (km² × 10³)	Reference
	Geologic Moment Rates		
Teton region	6.6×10^{22}	16.65	This study
Teton fault	6.3×10^{23}	0.63	This study
Hoback fault	6.0×10^{23}	0.40	This study
	Historic Moment Rates		
Helena, Montana (NOAA data) ($a = 2.45$, $b = 0.72$)	3.7×10^{22}	21.0	Qamar and Stickney (1983)
Southwestern Montana ($a = 2.7$, $b = 0.78$)	7.6×10^{22}	17.05	Qamar and Stickney (1983)
Teton fault ($a = 2.7$, $b = 1.0$)	3.4×10^{21}	6.0	Gilbert *et al.* (1982)
Hoback fault ($a = 2.4$, $b = 1.0$)	3.0×10^{21}	3.4	Gilbert *et al.* (1982)

The return period $T(M_0)$, for an earthquake with moment $M_0^{\min} \leqq M_0 \leqq M_0^{\max}$ can be estimated from Anderson (1979)

$$T(M_0) = \frac{\beta(M_0^{\max(1-\beta)} - M_0^{\min(1-\beta)})}{(1-\beta)\dot{M}_0^g(M_0^{-\beta} - M_0^{\max-\beta})} \tag{5}$$

where $\dot{M}_0^g$ is the geologic moment rate for a region. Using b values of 0.72 and 0.78 from Helena and Southwestern Montana, respectively, the return period for a $6.5 \leqq M_L \leqq 7.5$ earthquake in the Teton region was estimated to be 130 to 155 yr.

The average normalized geologic moment rate for the Teton fault was twice as large as any regional historic moment rate observed in the Intermountain seismic belt, suggesting that comparisons between moment rates for a single fault and moment rates for a region may not be meaningful. Wesnousky *et al.* (1983) suggest that seismicity on a single fault does not obey the Gutenberg-Richter relation, and have proposed that a maximum moment model be used to predict the return period of an earthquake along a single fault. Since the moment rate that we estimated for the Teton fault by assuming that the Gutenberg-Richter relationship was valid for the fault differed substantially from other observed moment rates in the intermountain region, we have used the approach of Wesnousky *et al.* (1983) to estimate return periods for a $M_L = 7.5$ earthquake along the Teton and Hoback faults. From Wesnousky *et al.* (1983)

$$T(M_0) = \frac{M_0^{\max}}{\dot{M}_0^g}. \tag{6}$$

Using the moment rates estimated for the 56-km-long segment of the Teton fault we obtain return periods of 800 to 1800 yr for a $M_L = 7.5$ earthquake. A return period of 1550 to 2360 yr is predicted for a similar magnitude earthquake along the Hoback fault.

Gilbert *et al.* (1982) have estimated a and b values for the Teton and Hoback faults using the scanty data on historical seismicity. We have computed normalized seismic moment rates from their a and b values (Table 4). Since Gilbert *et al.* (1982) used all earthquakes occurring within 30 km of the Teton and Hoback faults to estimate a and b values from historical seismicity, the areas used in the normalization (Table 4) have been adjusted accordingly.

Moment rates estimated from historical seismicity were 200 times smaller than our normalized geologic moment rate estimates for the Teton and Hoback faults. This suggests that the historical seismicity data used to calculate the a and b values does not reflect the long-term seismicity along the faults, that the seismicity has decreased significantly during historic time, or that seismicity along the faults does not obey a Gutenberg-Richter relationship.

Gilbert *et al.* (1982) also estimated an average return period of 3500 yr for a $M_L = 7.5$ earthquake along the Teton fault from average displacement rates and magnitude-displacement relationships using a fixed b value of 1.0. Comparisons between our geologic moment rates and historic moment rates of other regions in the Intermountain seismic belt suggest that b values of 0.7 to 0.8 are more appropriate for the Teton region.

It is important to emphasize that the return periods estimated in this study serve only as general estimates of the long-term seismicity for a region. The return periods should not be used for discrete predictions of seismicity without verification of the actual b and c values for the area.

A geologic strain rate for the Teton region was estimated from

$$\dot{M}_0 = 2\mu l_1 l_2 l_3 \dot{e}/k \tag{7}$$

where l_1 is the dimension of the region in the direction of maximum horizontal deformation, l_2 is the dimension normal to l_1 and l_3 is the depth, $\dot{e}$ is the strain rate, and k is an empirically determined constant. Using an average k value for Utah of 0.83 (Doser and Smith, 1982) and regional dimensions of $90 \times 185 \times 12$ km, a strain rate of 6.9×10^{-9}/yr was obtained. This rate is almost two times higher than the Wasatch Front rate of 3.5×10^{-9}/yr (Doser and Smith, 1982); however, it lies in the range of strain rates of 3.2×10^{-9} to 3.2×10^{-8}/yr estimated for the Basin and Range by Lawrence (1976).

As stated earlier, there may be as much as a factor of 2 error in the geologic moment rate estimates. Historic moment rate estimates may also be in error by about ±20 per cent. Nevertheless, these values are similar to those of other wellstudied areas of intraplate normal faulting, such as Utah, and indicate that the hazards associated with the occurrence of moderate to large earthquakes along normal faults of the Teton-Jackson Hole-southern Yellowstone region cannot be overlooked.

Conclusions

Using new and existing instrumental earthquake data, we have evaluated the seismicity of the Teton-Jackson Hole-southern Yellowstone region from 1973 to 1981. The majority of epicenters in the region do not appear to be associated with mapped traces of Quaternary faults. Similar conclusions were obtained by Smith and Sbar (1974) and Arabasz *et al.* (1980) for other regions of the southern Intermountain seismic belt. Seismicity in the Gros Ventre-Mount Leidy Highlands region may be related to reactivation of older basement structures. The Teton fault has been active at the small earthquake level along many of its segments, but there has been no significant seismicity along the north-central part of the fault; a segment that exhibits the greatest and most recent prehistoric displacement. Whether this observation is due to the possible episodic nature of seismicity along the segment or other factors is not known, but the possibility that this segment is locked and storing strain energy cannot be ruled out. The establishment of a permanent network to monitor the seismic activity in this area would help resolve this question.

Composite fault plane solutions for the region indicate predominantly east-west extension along normal faults. Although the northern part of the study region includes part of the Yellowstone caldera complex, there appears to be no major change in focal depth or focal mechanism as one approaches the southern boundary of the 600,000-yr-old caldera. One focal mechanism near the southern entrance of Yellowstone Park indicates east-west compression in a localized area near the 1.9 m.y. old Yellowstone caldera boundary.

Overall, seismicity in the Teton region shares many similarities with seismicity in other parts of the Intermountain seismic belt. For example, the Wasatch fault in Utah also shows spatial and temporal variations in seismicity along its length, with southern and northern segments having more seismic activity than some central segments (Arabasz *et al.*, 1980). Diffuse distributions of earthquakes that have no correlation with mapped active faults are found throughout Utah (Arabasz *et al.*, 1980), southeastern Idaho (Bones, 1978) and the northern Yellowstone-Hebgen Lake region (Smith *et al.*, 1977).

Geologic moment rates for the Teton area are comparable to historic moment rates observed in other parts of the Intermountain seismic belt, indicating that long-term seismicity in the Tetons is similar to that of the other regions. Large earthquakes ($6.5 \leqq M_L \leqq 7.5$) are estimated to occur in the Teton-Jackson Hole-southern Yellowstone area every 130 to 155 yr. Magnitude 7.5 earthquakes are estimated to occur along the Teton fault every 800 to 1800 yr.

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References

Anderson, J. G. (1979). Estimating the seismicity from geological structure for seismic-risk studies, *Bull. Seism. Soc. Am.* **69,** 135–158.

Arabasz, W. J., R. B. Smith, and W. D. Richins (1980). Earthquake studies along the Wasatch Front, Utah: network monitoring, seismicity, and seismic hazards, *Bull. Seism. Soc. Am.* **70,** 1479–1499.

Bones, D. G. (1978). Seismicity of the Intermountain seismic belt in southeastern Idaho and western Wyoming, and tectonic implications, *M.S. Thesis*, University of Utah, Salt Lake City, Utah, 100 pp.

Brune, J. N. (1968). Seismic moment, seismicity, and rate of slip along major fault zones, *J. Geophys. Res.* **73,** 777–780.

Christiansen, R. L. and H. R. Blank, Jr. (1972). Volcanic stratigraphy of the Quaternary rhyolite plateau in Yellowstone National Park, *U.S. Geol. Surv. Profess. Paper 516 E*, E14-E20.

Coffman, J. L. and C. A. von Hake (Editors) (1973). Earthquake history of the United States, U.S. Dept. of Commerce Publ. 41–1, 208 pp.

Doser, D. I. and R. B. Smith (1982). Seismic moment rates in the Utah region, *Bull. Seism. Soc. Am.* **72,** 525–551.

Gilbert, J. D., D. Ostenaa, and C. Wood (1982). Seismotectonic study of Jackson Lake Dam and Reservoir, Minidoka Project, Idaho-Wyoming, Preliminary Report, U.S. Bureau of Reclamation, Denver, Colorado, Boise, Idaho, 2 volumes, 110 pp.

Herrman, R. B., S.-K. Park, and C.-Y. Wang (1981). The Denver earthquakes of 1967–1968, *Bull. Seism. Soc. Am.* **72,** 731–745.

Hyndman, R. D. and D. H. Weichert (1983). Seismicity and rates of relative motion on the plate boundaries of western North America, *Geophys. J. R. Astr. Soc.* **72,** 59–82.

Kisslinger C., J. R. Bowman, and K. Koch (1981). Procedures for computing focal mechanisms from local $(SV/P)_z$ data, *Bull. Seism. Soc. Am.* **71,** 1719–1729.

Lawrence, R. D. (1976). Strike slip faulting terminates the Basin and Range Province in Oregon, *Bull. Geol. Soc. Am.* **87,** 846–880.

Lee, W. H. K. and J. C. Lahr (1975). HYPO71 (revised): a computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *U.S. Geol. Surv., Open-File Rept. 75-311,* 133 pp.

Love, J. D. and J. M. de la Montagne (1956). Pleistocene and recent tilting of Jackson Hole, Teton County, Wyoming in *Wyoming Geol. Assoc. Guidebook, Eleventh Ann. Field Conf.*, Jackson Hole, Wyoming, 169–178.

Love, J. D. and J. C. Reed, Jr. (1969). *Creation of the Teton Landscape—The Geologic Story of Grand Teton National Park*, Grand Teton Natl. Hist. Assoc., Moose, Wyoming, 120 pp.

Love, J. D. and J. C. Reed, Jr. (1975). Geologic map of Teton Village Quadrangle, *U.S. Geol. Surv., Open-File Rept. OF-75-335.*

Love, J. D. and D. W. Taylor (1962). Faulted Pleistocene strata near Jackson, northwestern Wyoming, in Short Papers in Geology, Hydrology and Topography, *U.S. Geol. Surv. Profess. Paper 450-D*, D136–D139.

Love, J. D., J. C. Reed, Jr., R. L. Christiansen, and J. R. Stacy (1973). Geologic block diagram and tectonic history of the Teton region. *U.S. Geol. Surv., Misc. Geol. Investigations Map I-730.*

Molnar, P. (1979). Earthquake recurrence intervals and plate tectonics, *Bull. Seism. Soc. Am.* **69,** 115–133.

Qamar, A. and M. C. Stickney (1983). Montana earthquakes 1869–1979, Historical seismicity and earthquake hazard, *Montana Bureau of Mines and Geology, Memoir* **51,** 80 pp.

Schilly, M. M. (1979). Lithospheric structure of an intraplate hotspot, the Yellowstone-Snake River Plain region, *M.S. Thesis*, University of Utah, Salt Lake City, Utah, 170 pp.

Schilly, M. M., R. B. Smith, L. W. Braile, and J. Ansorge (1982). The 1978 Yellowstone-Snake River Plain seismic profiling experiment: data and upper crustal structure of the Yellowstone region, *J. Geophys. Res.* **87,** 2692–2704.

Smith, R. B., R. T. Shuey, R. C. Friedline, R. M. Otis, and L. B. Alley (1974). Yellowstone hot spot: new magnetic and seismic evidence, *Geology* **2,** 451–455.

Smith, R. B., J. R. Pelton, and J. D. Love (1976). Seismicity and the possibility of earthquake related landslides in the Teton-Gros Ventre-Jackson Hole area, Wyoming, *Contributions to Wyoming, Geology* **14,** 57–64.

Smith, R. B., R. T. Shuey, J. R. Pelton, and J. P. Bailey (1977). Yellowstone hot spot: contemporary tectonics and crustal properties from earthquake and aeromagnetic data, *J. Geophys. Res.* **82,** 3665–3676.

Tibbetts, B. L., J. C. Behrendt, and J. D. Love (1969). Seismic refraction measurements in Jackson Hole, Wyoming, *Bull. Geol. Soc. Am.* **80,** 1109–1122.

U.S. Geological Survey (1972). Geologic map of Yellowstone National Park, *Misc. Geol. Investigations Map I-711.*

Wesnousky, S. G., C. H. Scholz, K. Shimazaki, and T. Matsuda (1983). Earthquake frequency distribution and the mechanics of faulting (submitted for publication).

Witkind, I. J. (1975). Preliminary map showing known and suspected active faults in Wyoming, *U.S. Geol. Surv., Open-File Rept. OF-75-279.*

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