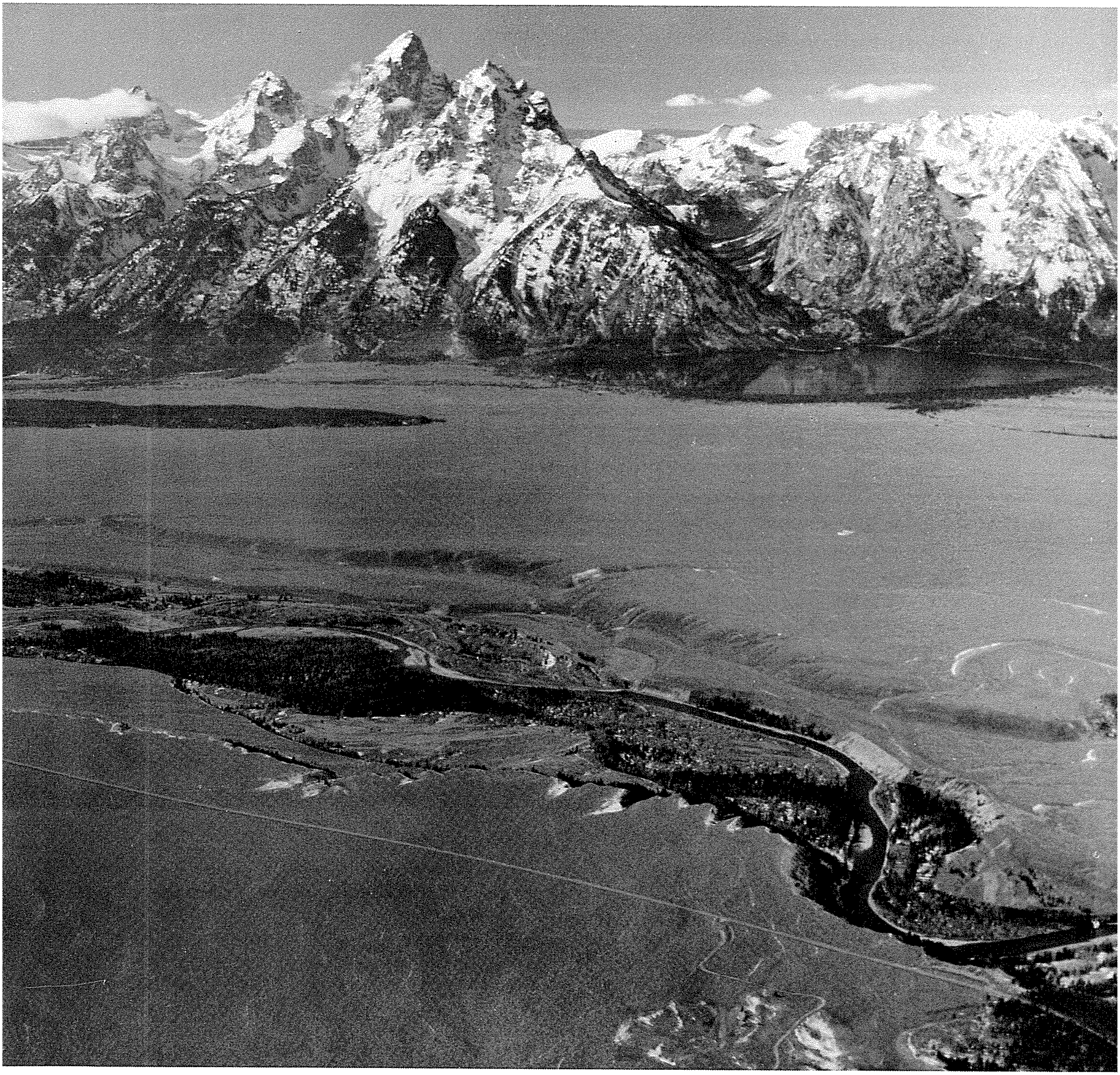

Frontispiece. Aerial view of the Teton Range (looking southwest) showing the spectacular topographic relief (~2,100 m) of the range due pimarily to 6-9 km of stratigraphic offset along the east-facing Teton normal fault. The Quaternary expression of the Teton fault is at the base of the range and generally extends along the top of the wooded slopes between Garnet Canyon on the left and Jenny Lake on the right. The Snake River at Deadman's Bar is shown in the lower left foreground. The valley of Jackson Hole (foreground) occupies the down-dropped, hanging-wall sediment basin now filled by lake beds, alluvium, and glacial deposits. Photograph courtesy of David R. Lageson, Montana State University.

The Teton fault, Wyoming: seismotectonics, Quaternary history, and earthquake hazards

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Abstract

The more than 2 km of topographic relief of the spectacular Teton Range, Wyoming, is attributed to uplift along the Teton fault. Movement on this major, range-bounding normal fault is thought to have begun as early as 5 to 13 million years ago and the fault has been active during Quaternary time, producing well-preserved fault scarps up to 50 m high and over 55 km long. These young scarps offset Pinedale-age (~14 ka) glacial deposits and younger fluvial and alluvial deposits. The total stratigraphic offset of the Teton fault is estimated to be 6 to 9 km. The youthful nature and magnitude of Quaternary faulting demonstrate its capability for producing large, scarp-forming earthquakes despite evidence that the Teton fault has been seismically quiescent in historic time. We believe that a 4.1 m vertical displacement in near-surface alluvium and glacial deposits, observed in a trench exposure on the southern segment of the Teton fault, represents the most recent displacement(s) on the fault and is the product of two large Holocene earthquakes. The oldest of these events occurred 7,175 ± 190 years ago (radiocarbon date) and resulted in 2.8 m of slip, whereas a younger and yet undated event produced a 1.3 m slip. Stratigraphic displacements of Quaternary volcanic rocks and results from the trench suggest Holocene slip rates of 0.45 to 1.6 mm/yr for the Teton fault. These rates are consistent with a range of recurrence intervals for large, scarp-forming earthquakes of 1,600 to 6,000 years. An area of unusual topographic subsidence, up to 26 m, was located 0.5 to 2 km east of the central part of the Teton fault and is similar to a pattern of down-to-west tilt of the valley floor against the Teton fault in southern Jackson Hole. This anomalous pattern of subsidence may reflect, in part, hanging-wall deformation associated with large prehistoric earthquakes.

To assess the contemporary deformation of the Teton fault, a 22 km-long profile of 50 precisely surveyed benchmarks was established across the Teton fault in 1988 and surveyed in 1988 and 1989 in a cooperative project with the University of California, Santa Barbara. During that period, the valley of

Smith, R.B., Byrd, J.O.D., and Susong, D.D., 1993, The Teton fault, Wyoming: seismotectonics, Quaternary history, and earthquake hazards, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., editors, Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 628-667.

Jackson Hole (hanging wall) rose up to 8 mm relative to the Teton Range (footwall), opposite to the pre-seismic deformation expected for a normal fault. This unexpected deformation may have resulted from non-tectonic mechanisms, such as near-surface inflation due to alluvial expansion from groundwater introduced during the refilling of Jackson Lake, or tectonic processes such as aseismic reverse creep.

We consider that the Teton fault has the potential for large scarp-forming earthquakes of $M_S = 7.2 \pm 0.3$. Earthquakes of this size could damage or destroy lifelines, produce strong ground motion, and trigger landslides and snow and rock avalanches. Moderate magnitude (M_S=5.5 to 6.3), nonsurface-rupturing earthquakes are also important because of their more frequent occurrence, but they would affect smaller areas than less frequent, larger earthquakes.

Introduction

The Teton fault is an important element of the 1,300 km-long Intermountain seismic belt (referred to hereafter as ISB), an intraplate zone of seismicity (**Figure 1**) that extends northward from southern Utah, through eastern Idaho and western Montana, and encompasses western Wyoming and the Teton fault (Smith and Sbar, 1974; Smith and Arabasz, 1991). The pre-Quaternary expression of the Teton fault extends north-south for up to 70 km on the east side of the Teton Range, and it has a total stratigraphic separation estimated to be from 6 to 9 km (Love and Reed, 1971). A striking aspect of this major fault is a string of well-preserved fault scarps in Quaternary glacial deposits that extend 55 km along the base of the range (**Frontispiece**). The Teton fault is considered by us as the single most important factor contributing to the ~2,150 m (~7053 feet) of topographic relief and therefore to the spectacular scenery of the Teton Range—the essence of Grand Teton National Park.

The seismotectonic significance of the Teton fault is evident when it is compared to similar range-front normal faults associated with three large scarp-forming earthquakes in the Basin and Range province in historic time: (1) the Dixie Valley fault, associated with the M_S = 6.8, 1954, Dixie Valley, Nevada, earthquake (Slemmons, 1957; Doser, 1988); (2) the Hebgen Lake and Red Canyon faults, associated with the M_S = 7.5, 1959, Hebgen Lake, Montana, earthquake (Myers and Hamilton, 1964; Doser, 1985); and (3) the Lost River fault, Idaho, site of the M_S = 7.3, 1983, Borah Peak, Idaho, earthquake (Doser and Smith, 1985; Richins and others 1987; Crone and others, 1987). These well-studied events nucleated at mid-crustal depths of 15 ± 5 km and were the result of rupture on 45° to 60° dipping, planar normal faults (see **Figure 1** for locations of the Hebgen Lake and Borah Peak earthquakes). Hanging-wall subsidence associated with these large earthquakes was as large as 6 m and surface ruptures extended up to 34 km in length. The similarities among these three earthquakes have led to a conceptual working model for normal-faulting earthquakes (Smith and others, 1985; King and others, 1988; Smith and Arabasz, 1991) that enables us to hypothesize the magnitude and extent of surface rupture and ground deformation that may accompany large scarp-forming earthquakes, such as those expected on the Teton fault.

We report here the results of a four-year study focused on the seismotectonics, Quaternary history, and earthquake hazards of the Teton fault. Preliminary results of this work were given by Susong and others (1987), Byrd and others (1988), and Smith and others (1990a, b, c). Our research was supported by the University of Wyoming-National Park Service Research Center, U.S. Geological Survey, and Geological Survey of Wyoming.

Regional tectonic setting

The structural evolution of the Teton Range and the Teton fault (**Figure 2**) has been influenced by four major orogenic tectonic-volcanic events: (1) Precambrian deformation, metamorphism, and plutonism

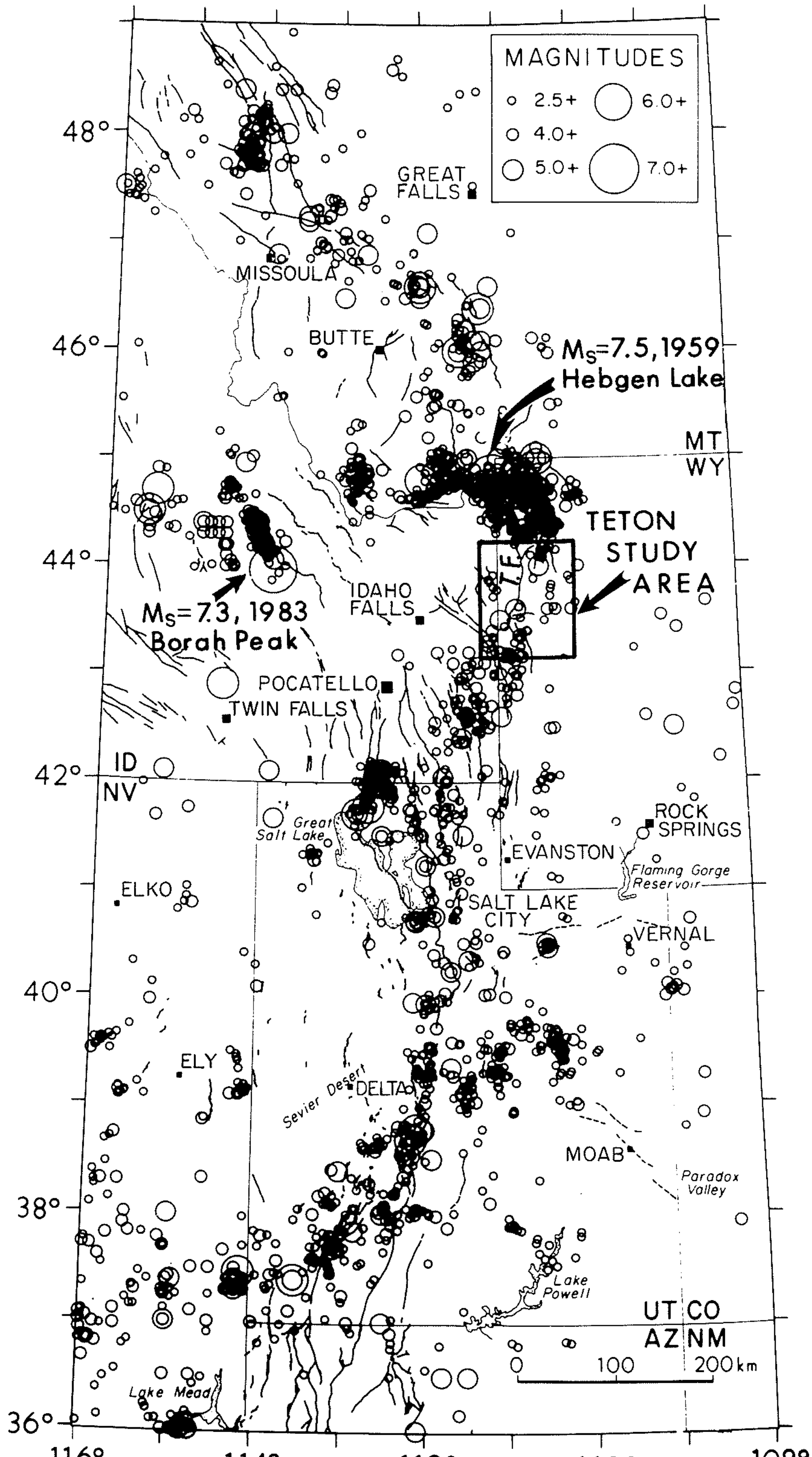


Figure 1. Seismicity of the Intermountain seismic belt for 1850 through 1985 (from Smith and Arabasz, 1991). Teton fault study area outlined by box.

forming the core of the range; (2) Mesozoic to early Tertiary crustal shortening, including thrust faulting and folding of the Wyoming-Idaho thrust belt and the Laramide foreland provinces; (3) late Tertiary to Quaternary, Basin and Range epeirogeny accompanied by east-west crustal extension and normal faulting; and (4) late Tertiary-Quaternary silicic volcanism and crustal uplift and subsidence associated with the Yellowstone-Snake River Plain volcanic system. These diverse tectonic regimes have no doubt had a profound effect on the Teton region, but we believe the late Tertiary crustal extension attributed to Basin and Range tectonism has had the dominant influence on the topographic development of the Teton Range and on the structural evolution of the Teton normal fault (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket).

On a more regional scale, the seismic quiescence of the eastern Snake River Plain, a late Tertiary, bimodal rhyolite-basalt province, with its pronounced seismically active "shoulders" (**Figures 4** and **5**), led several workers (Smith and others, 1985, 1990b; Smith and Braile, this volume; Anders and others, 1989; Pierce and Morgan, 1990) to postulate the effect of the Yellowstone hotspot on the seismotectonics of the central Intermountain region. Smith and others (1985, 1990b), Smith and Braile (this volume), and Anders and others (1989) suggest that a lithospheric thermal disturbance associated with the Yellowstone hotspot extends outward from the center of the Snake River Plain, influencing the regional stress field and resulting in an aseismic central region and a roughly parabolic-shaped pattern of earth-

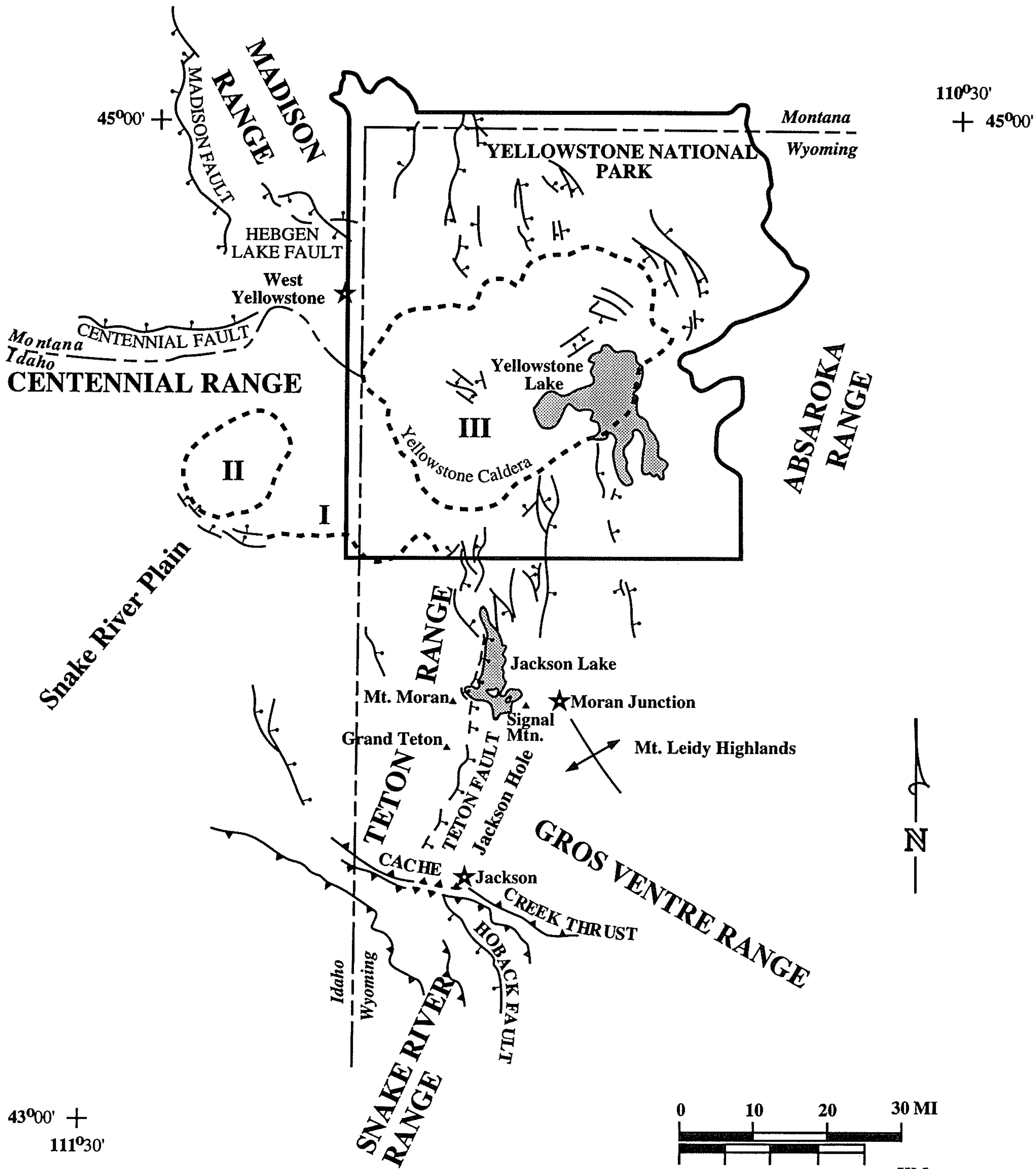


Figure 2. Tectonic index map of the Teton Range and Yellowstone Plateau of Wyoming, Idaho, and Montana. Ages of Yellowstone calderas (outlined with dashes): I = 2.0 Ma, II = 1.2 Ma, and III = 0.6 Ma. (Standard symbols for normal faults, thrust faults, and anticline.)

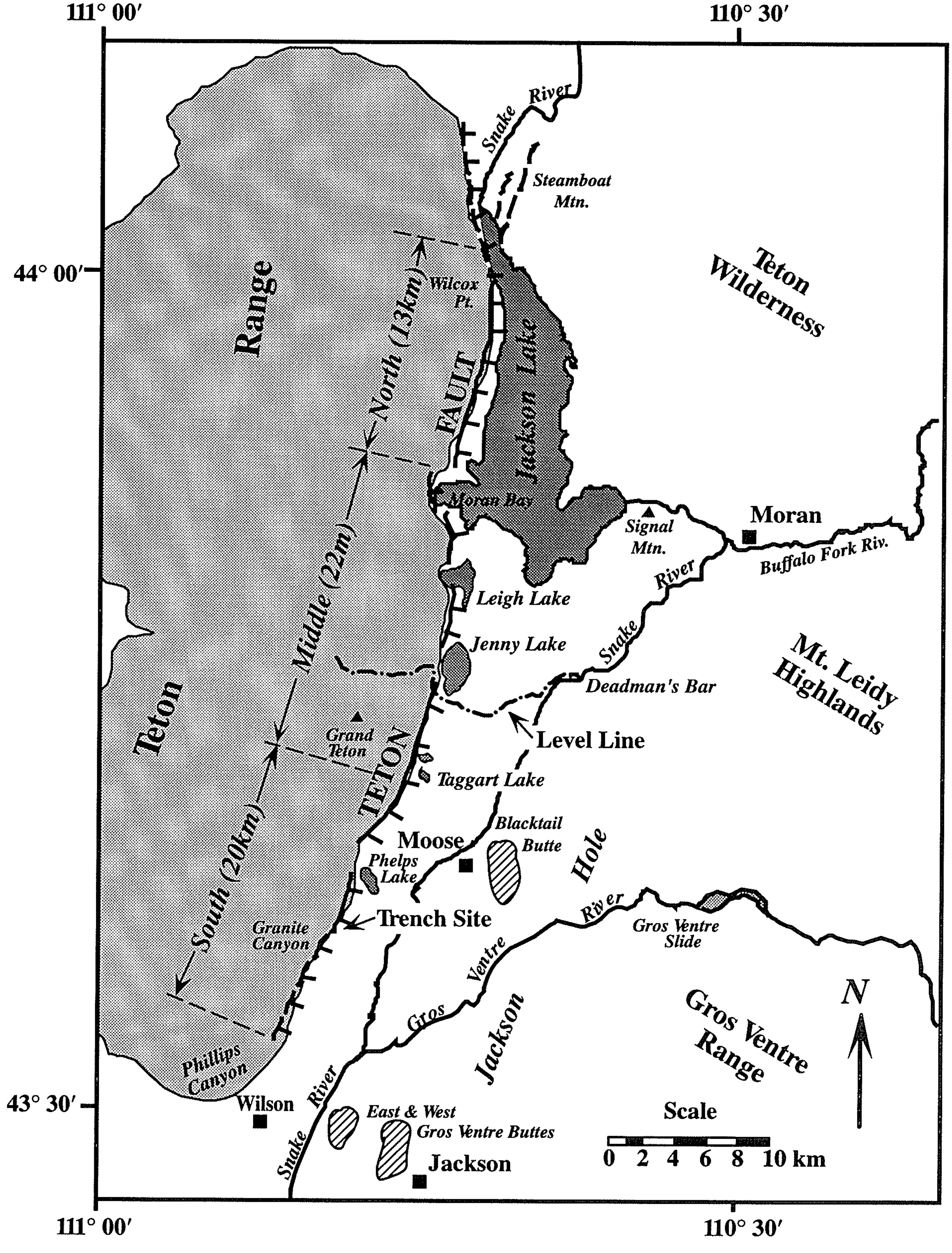


Figure 3. Map of the Teton Range-Jackson Hole region showing the Quaternary expression of the Teton fault and proposed segment boundaries. The map also shows key geographic features cited in the text. Light grey pattern is area of Precambrian outcrop. Cross-hachured areas are outcrops of Palozoic rocks in Jackson Hole.

quakes surrounding the volcanic province. The Teton region is located within the eastern branch of the parabolic-shaped area of seismicity located east of the Snake River Plain (**Figure 4**). It is also east of a belt of late Cenozoic normal faulting that appears to have been relatively inactive throughout Holocene time (Scott and others, 1985; Smith and others, 1985).

Evidence for Late Cretaceous initiation of deformation along the Teton Range was provided by a study of apatite fission-track age-determinations taken from samples acquired along the eastern range front (Roberts and Burbank, 1988, 1993). They determined dates of 85 to 25.8 Ma with decreasing sample elevation and inferred uplift of 1 to 1.5 km of the Teton Range in the Late Cretaceous. Roberts and Burbank (1988, 1993) further speculated that the post-30 Ma uplift of the Teton Range was represented by approximately 2 km of offset of the 2 Ma Huckleberry Ridge Tuff.

Notably, earlier studies of the Teton region by Blackwelder (1915) and Horberg and others (1955) pointed out that the Teton fault may be a fault-line scarp, an hypothesis that it is consistent with the Late Cretaceous uplift suggested by Roberts and Burbank (1988, 1993). Furthermore, Lageson (1992) suggested that the Teton fault may reflect reactivation on the northeast-dipping Cache Creek thrust (**Figure 2**) that flanked a Laramide basement high. If these hypotheses are correct, then the Teton Range has had a complex history of pre-Tertiary uplift and Tertiary erosion, followed by Plio-Pleistocene range uplift and valley subsidence along the Teton fault.

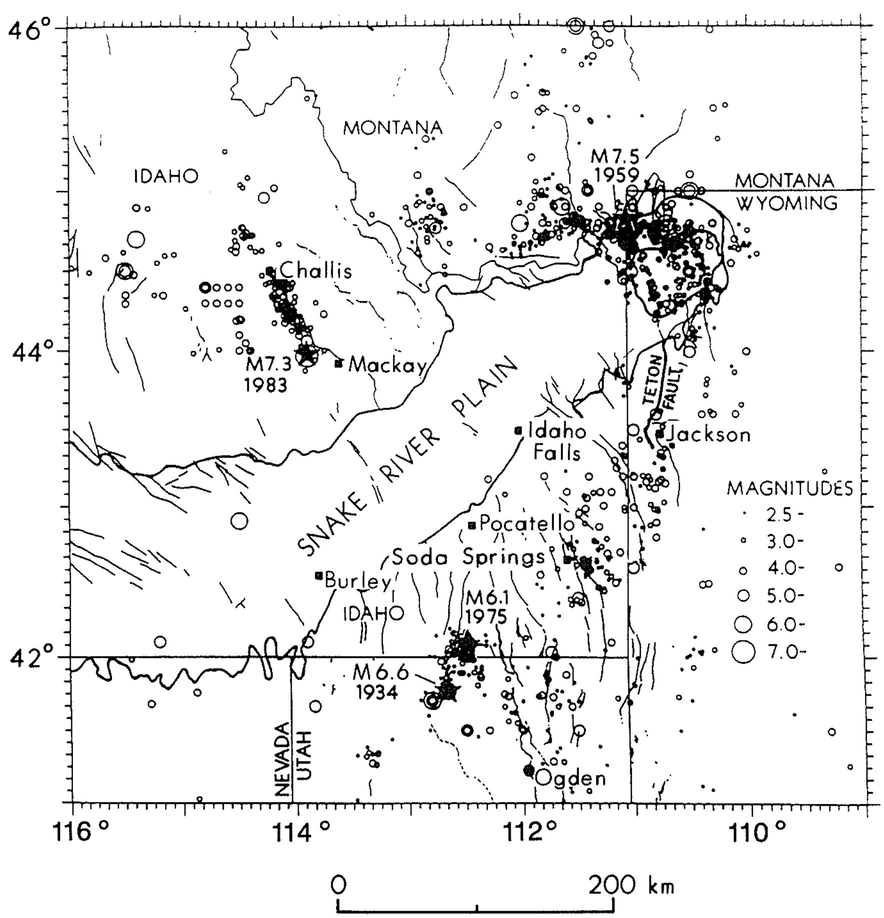


Figure 4. Regional seismicity of Yellowstone-Snake River Plain-Teton region for the period ~1900 to 1985. Map modified from Smith and others (1990a) and Smith and Arabasz (1991).

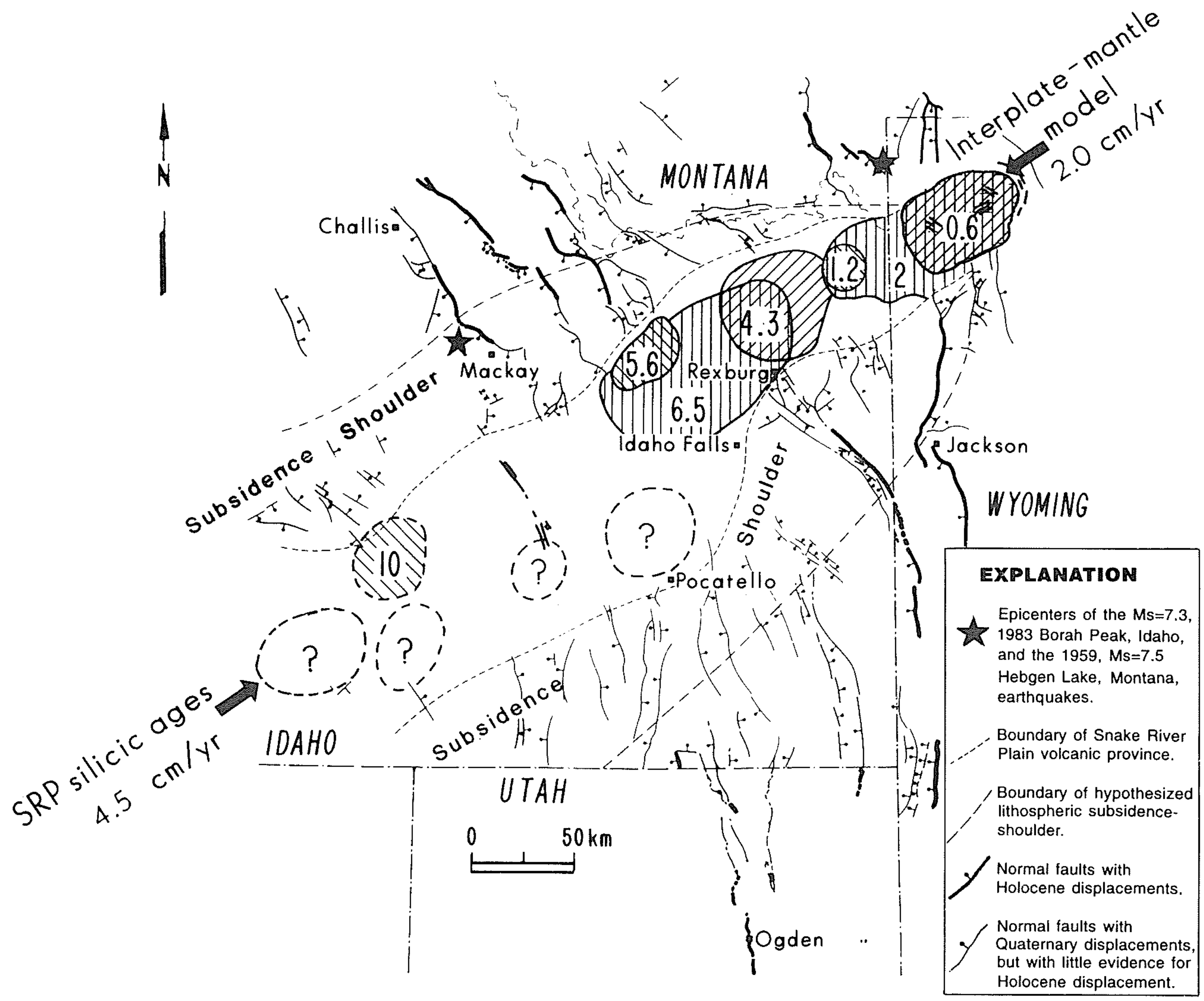


Figure 5. Distribution of calderas (with ages in millions of years), late Cenozoic normal faults, and deformation zones associated with the Snake River Plain-Yellowstone volcanic system. The arrow at Yellowstone is the direction of motion of the North American plate relative to the Yellowstone hotspot with an absolute velocity of ~2 cm/yr, and the arrow at the southwest end of the Snake River Plain (SRP) is the direction of progressively younger silicic volcanism of 4 cm/yr (after Smith and Braile, this volume). Map modified from Smith and others (1990a) and Smith and Braile (this volume).

General geology

The geological setting of the Teton region is well known and is not described here except to point out the general features that relate to our study. The reader is referred to discussions of the geology and tectonics of the Teton Range and the Jackson Hole area by Love (1956), Love and Reed (1971), Love and others (1972), and Love (1977).

The Teton Range consists primarily of a core of Precambrian igneous and metamorphic rocks including quartz monzonite, gneiss, and diabase (Reed, 1973; Reed and Zartman, 1973). These crystalline basement rocks are overlain by westward-tilted Paleozoic strata and Quaternary silicic volcanic rocks that form the western dip slope of the Teton Range

(Love and Reed, 1971; Love and others, 1992). **Figure 6** shows our interpreted west-east geologic cross section of the Teton Range and Jackson Hole with the corresponding aerial view of the Teton Range looking north. On the east side of the Teton Range, a 70 km-long valley, Jackson Hole, occupies the hanging wall of the Teton fault and appears to be underlain by an asymmetric, west-dipping Tertiary-Quaternary basin. The Quaternary strata are fluvial, glacial, and volcaniclastic deposits and are underlain by Tertiary lacustrine, fluvial, and volcaniclastic units. A relatively continuous section of Paleozoic and Mesozoic sedimentary rocks is thought to underlie Jackson Hole based on the results of geophysical surveys (Behrendt and others, 1968; Tibbetts and others, 1969) and on exploratory wells in the Gros Ventre Range and the Mount Leidy Highlands (**Figure 6b**). The Paleozoic strata are well exposed on the west flank of the Teton Range and serve as a geometric marker of the uplifted and westward tilted hanging wall of the Teton fault.

Although several bedrock buttes, consisting of westward- to vertically-dipping Paleozoic and Tertiary sedimentary and volcanic rocks are exposed in the central and southern parts of Jackson Hole (Love, 1956; Love and Albee, 1972; Love and Love, 1978; Love, unpublished maps), the structural configuration and thicknesses of formations underlying the basin are poorly known. The estimated total stratigraphic offset of the Teton fault (6 km, **Figure 6b**) could be in error by as much as ± 50% or more, especially if our assumptions of a planar-dipping fault and formation geometry and thicknesses are incorrect.

The floor of Jackson Hole is marked by widely distributed Pleistocene glacial deposits that provide evidence for at least two periods of Pleistocene glaciation. These were the Bull Lake (100 to 150 ka) and Pinedale (14 to 30 ka) stages that filled Jackson Hole with up to 790 m of ice (Porter and others, 1983; Pierce, 1979; Pierce and Good, 1990; Smith and others, this volume). The younger Pinedale age glaciers flowed south and southwest from the Yellowstone ice cap, depositing the terminal moraines that form the southern margin of Jackson Lake. Smaller Pinedale valley glaciers carved the steep canyons in the Teton Range and produced terminal moraine complexes at the canyon mouths that have been offset by the Teton fault (for example, see the first discussions of these features in Fryxell, 1938a,b). The lateral extent and configuration of the fault scarps that offset these and younger deposits define the Quaternary trace of the fault and were the focus of our first-year mapping project.

The Snake River and the streams emanating from the Teton Range form a rather unusual drainage pattern across the floor of Jackson Hole (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). The Snake River is the main drainage of Jackson Hole and exits Jackson Lake at its southeast margin, north of Signal Mountain. It follows a course along the eastern side of Jackson Hole until the channel works its way to the west side of the valley at the southern end of the valley. A surprising aspect of the fluvial drainage is the generally southward flow of several streams exiting the canyons of the central and southern parts of the Teton Range. Rather than draining eastward into the Snake River, these streams appear to have been diverted southward from Leigh Lake and south of Phelps Lake along the western side of Jackson Hole (**Sheet 1**, Smith, Byrd, and Susong, map pocket). The geomorphic features responsible for the diversion of these streams may be due to damming by glacial and fluvial features. However, we suggest that the diversion appears to be in part related to hanging-wall subsidence associated with prehistoric earthquakes and thus agree with Love and Montagne (1956) who suggested that prehistoric earthquakes on the Teton fault played a significant role in developing this unusual drainage pattern at the south end of the Teton fault.

In contrast to the youthful Teton Range, the Gros Ventre Range, east of Jackson Hole (**Figures 2** and **3**), evolved as part of the Wyoming foreland province during the Laramide orogeny (Nelson and Church, 1943). The Gros Ventre Range consists of a core of Precambrian igneous rocks that underlies a generally continuous Paleozoic, Mesozoic, and Tertiary sedimentary section. The rocks are exposed in a series of north-northwest-trending folds that developed in response to uplift along the Cache Creek thrust and a series of high-angle reverse faults within the range (e.g., Nelson and Church, 1943; Simons and others, 1981; Lageson, 1987).

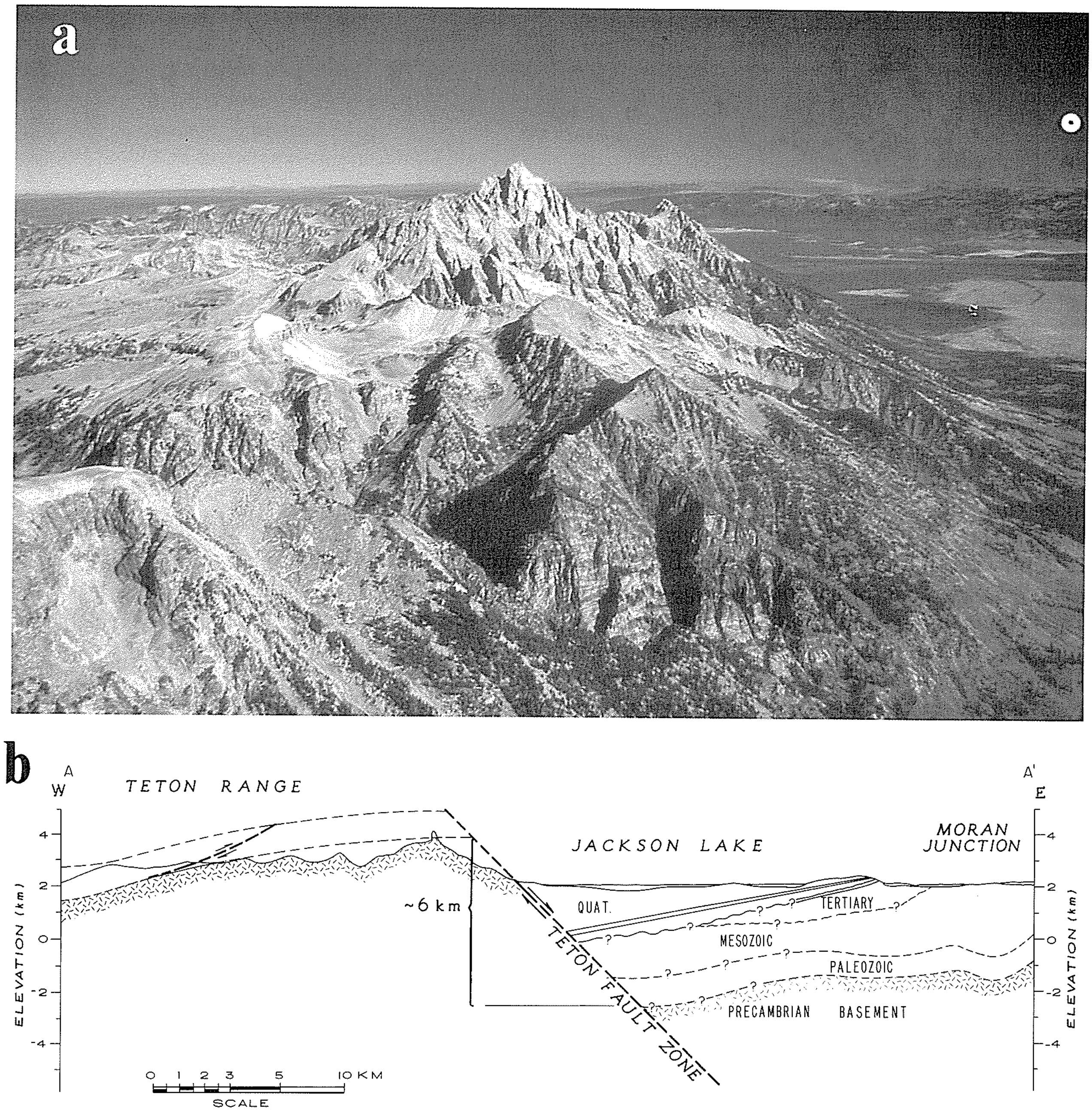


Figure 6. (a) Aerial view of the Teton Range and the Grand Teton looking north. (This picture corresponds to the cross-section in Figure 6b.) The hanging-wall valley of Jackson Hole (upper right) is bounded on the west by the uplifted Teton Range. Note the west-dipping Paleozoic strata to left of the Grand Teton (photograph by Robert B. Smith). (b) Schematic geologic cross section of the Teton Range and Jackson Hole showing a total stratigraphic offset of ~ 6 km of the Teton fault. The total displacement was estimated from offsets of the Cambrian Flathead Sandstone exposed on top of Mt. Moran to its projected depth in Jackson Hole. The subsurface configuration of Mesozoic and Paleozoic sediments beneath Jackson Hole is based on a projection of limited outcrop data and well data taken from Love and others (1992), Behrendt and others (1968), and Tibbetts and others (1969).

Seismicity of the Teton region

The Teton Range lies within the central part of the ISB (**Figures 1** and **4**). This zone of intraplate seismicity is characterized by a diffuse zone of epicenters, up to 200 km wide, that generally do not correlate with the surface traces of Quaternary faults (Smith and Arabasz, 1991). The ISB represents the general boundary between the Basin and Range province on the west and the Colorado Plateau-Middle Rocky Mountains on the east. Focal mechanisms and patterns of Quaternary faulting in the ISB commonly reflect normal to oblique-slip faulting and focal depths are shallow, seldom exceeding 15 km (Smith and Sbar, 1974; Smith and Arabasz, 1991). Studies of focal mechanisms and seismic moment[1] rates of historical earthquakes suggest that contemporary deformation of the Teton region is characterized by general east-west crustal extension accommodated on normal- to oblique-slip faults, but at relatively low horizontal deformation rates of 0.01 mm/yr or less (Eddington and others, 1987; Doser and Smith, 1983; Wood, 1988). These rates are much lower than those determined for other areas in the ISB (Eddington and others, 1987) and are also much lower than the long-term slip estimated for the Teton fault during Quaternary time.

The central ISB has experienced some of the largest earthquakes in the conterminous United States (**Figures 1** and **4**). These include the $M_S = 7.5$, 1959, Hebgen Lake, Montana, earthquake. This is the largest historic earthquake in the Rocky Mountains and it was located only 90 km northwest of the Teton Range. Most recently, the $M_S = 7.3$, 1983, Borah Peak, Idaho, earthquake occurred 200 km west of the Teton Range on the northwest side of the Snake River Plain. In addition, earthquakes as large as $M_L = 6.1$ and extensive earthquake swarms characterize the Yellowstone Plateau. Earthquakes of the Yellowstone volcanic system begin just 10 km north of the Teton Range (Smith and Arabasz, 1991).

Historical seismicity

Earthquakes have been commonly reported by inhabitants of Jackson Hole since the late 1800s (Blackwelder, 1926). Until about the 1950s, earthquake locations in the western U.S. were based upon the personal felt reports of ground-shaking based on the Modified Mercalli intensity scale and are considered accurate to ± 50 km (Smith and others, 1976). Earthquakes in the Teton region from the 1950s to the early 1960s were recorded by a few seismographs scattered throughout the western U.S., which, along with the intensity reports, provided only a marginal increase in epicenter accuracy. Following the installation of networks of seismographs throughout the western U.S. beginning in 1962, epicenter accuracy increased to about ± 10 km for the Teton region (Smith and Arabasz, 1991). When the more densely spaced, temporary and permanent seismograph networks were installed in the Teton-Yellowstone area beginning the early 1970s, the epicenter accuracy increased to ± 1 to 2 km (Doser and Smith, 1983; Smith and Arabasz, 1991). This is the accuracy of the current U.S. Bureau of Reclamation network coverage of the Teton region (Wood, 1988), making these data sufficiently accurate for seismotectonic assessments.

The historical seismicity of the Teton region is characterized by a relatively large number of earthquakes reported by the small and isolated population of Jackson Hole from the early 1900s to the early 1930s. Several earthquakes up to intensity VI that caused minor damage throughout this period were reported in the Gros Ventre Canyon (Blackwelder, 1926; Fryxell, 1933; Gale, 1940; Coffman and Von Hake, 1973). However, after about 1933, the incidence of felt earthquakes in the Teton area perceptibly decreased in Jackson Hole and no significant ground shaking was reported until 1959, when the $M_S = 7.5$, Hebgen Lake, Montana, earthquake produced significant shaking throughout the valley. Love (1973) documented several earthquakes that were felt in the area in 1968, 1970, and 1972; however, no felt events were reported in the Jackson Hole area from 1972 to 1979 (see U.S. Geological Survey's annual publications *United States Earthquakes, 1985*, Stover and Brewer, 1991). From 1979 to the present, small to moderate shocks, some as large as $M_L = 4.6$, were reported in the southern Jackson Hole area, although the most recent U.S. Geological Survey earthquake compilation is only current through 1985. These felt events were recorded on regional networks, and the locations of their epicenters are poorly known, precluding their assignment to specific faults.

[1] Seismic moment is a term that quantitatively describes the size of an earthquake by its length, width, and coefficient of shear rigidity.

Regional earthquake monitoring

Earthquake monitoring, focused on the Teton Range and Jackson Hole, was initiated by the University of Utah in 1973 (Smith and others, 1977) and was conducted intermittently during summer field seasons through 1981 (Doser and Smith, 1983). These surveys used portable seismographs and located earthquakes as small as approximately M_L ~ 1.0; however, calibrated magnitudes were not determined for these events. The U.S. Bureau of Reclamation established a permanent seismograph network surrounding Jackson Lake, the Palisades reservoir, Idaho, and west side of the Teton Range in the summer of 1986 (Wood, 1988). The U.S. Bureau of Reclamation network includes 22, short-period, vertical-component seismographs centrally recorded in Denver, Colorado (Wood, 1988).

Epicenter data from the University of Utah temporary networks, combined with data from the U.S. Bureau of Reclamation permanent network for 1986 to 1988, illustrate the distribution of earthquakes in the Teton region in recent years (**Figure 7**). The epicenters define a diffuse pattern of small earthquakes that extends at least 80 km northeastward from the Wyoming and Snake River Ranges to an area west of the Hoback Junction and northeastward into the Gros Ventre Range-Mt. Leidy area. An area of sparse earthquakes is also noted on the west flank of the Teton Range. Note the general lack of small-magnitude earthquakes on the Teton fault and in Jackson Hole, extending north from the vicinity of Moose for at least 50 km (**Figure 7**). The epicenters shown in the northern part of **Figure 7** are at the southern end of a band of persistent north-trending seismic activity that extends 30+ km northward beneath the southern part of the Yellowstone caldera (**Figure 4**). These epicenters may reflect earthquakes on a buried extension fault or zone of weakness related to the Teton fault now covered by Quaternary volcanic rocks in Yellowstone National Park (Smith, 1988; Smith and others 1990b).

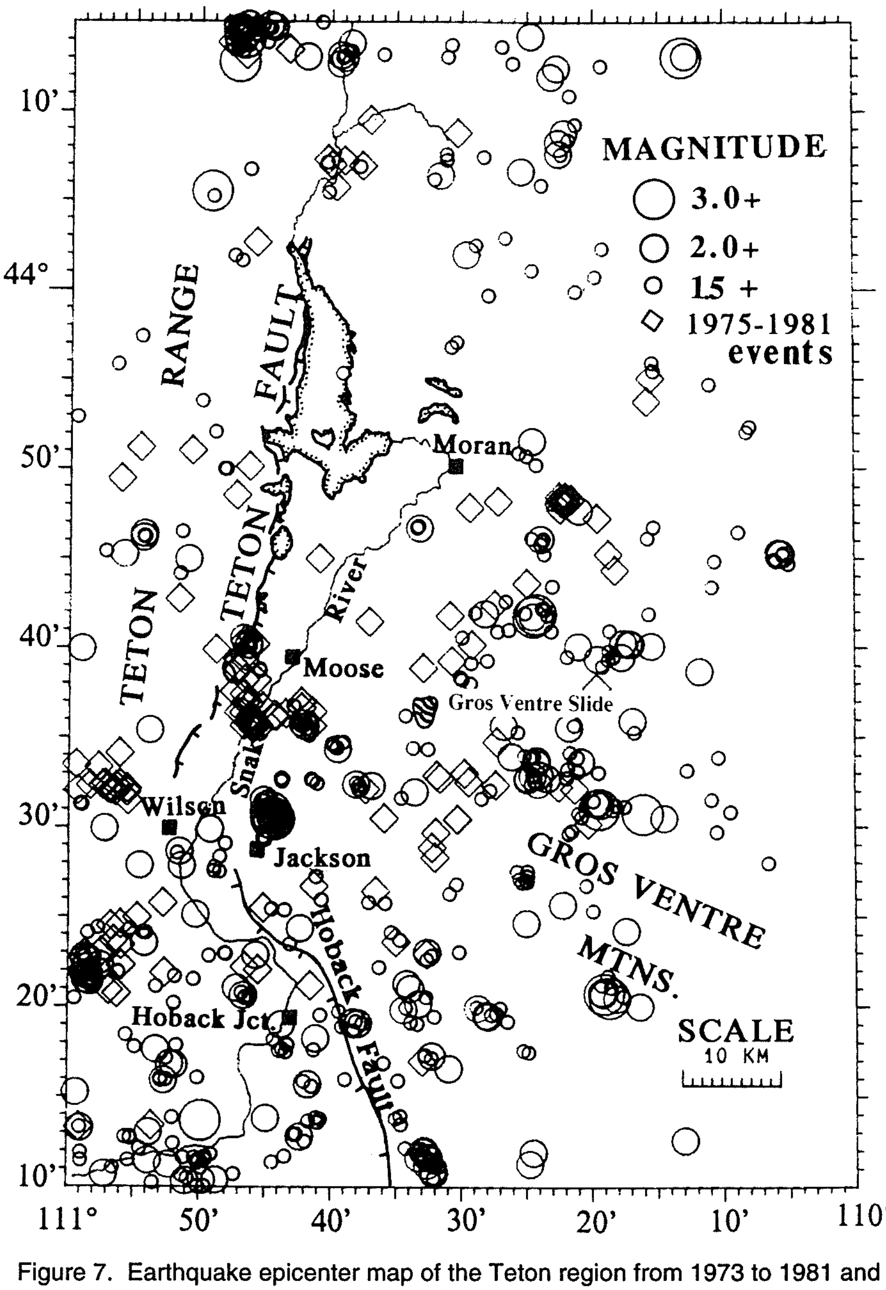


Figure 7. Earthquake epicenter map of the Teton region from 1973 to 1981 and 1983 to 1988. [1973 to 1981 data from the University of Utah (Smith and others, 1976; Doser and Smith, 1985; University of Utah unpublished data); and 1986 to 1988 data from the U.S. Bureau of Reclamation (Wood, 1988).]

Doser and Smith (1983) noted a correlation of epicenters in the Gros Ventre Range-Mt. Leidy area with a 5.5 to 7 km-deep, Laramide thrust zone identified from seismic reflection profiles. Although Doser and Smith (1983) could not definitely show that the earthquakes were associated with thrust faults, their close spatial correlation suggests that the background seismicity of the Gros Ventre region may result, in part, from displacements associated with pre-existing zones of weakness.

A notable north-trending belt of earthquakes near the southern end of the Teton fault and the two distinct clusters of epicenters between Jackson and Moose (**Figure 7**) are the likely sources of several felt earthquakes reported in Jackson in the late 1980s. The foci of these tremors are generally less than 5 km (Wood, 1988) and the projection of a 45°-60° eastward-dipping Teton fault into this area places the fault plane at depths of 10 to 15 km. The shallow foci of these earthquakes are therefore not on the eastward projection of the Teton fault and may be related to movement on related, yet unknown, structures in the hanging wall.

The pattern of historic earthquakes of the central ISB shows that the Teton fault has been notably aseismic for magnitudes $M_L \geq 2$ (**Figure 8**) for the period 1959 to 1989. The very low regional strain rate (Eddington and others, 1987) and the general seismic quiescence of the Teton area compared to the rest of the ISB led Smith (1988) to suggest a possible "gap" in the historic seismicity of this region at the $M_L > 3$ level. If his interpretation is valid, the Teton fault may be "locked" and the area of seismic quiescence may be expected to reactivate with moderate to large earthquakes in the future. However, possible alternate interpretations for the aseismic nature of the Teton fault include: (1) the Teton fault is no longer active and therefore is not storing significant strain energy required for earthquake nucleation. However, based on the Holocene history of faulting and the long-term geologic record, we have no reason to believe that the Teton fault is not active; (2) the main belt of regional seismicity may have migrated eastward onto unknown structures in the Gros Ventre Range, thereby relieving stress accumulation on the fault; and (3) the period of historic seismological observations may not be sufficiently long to accurately assess the temporal pattern of the long-term seismicity .

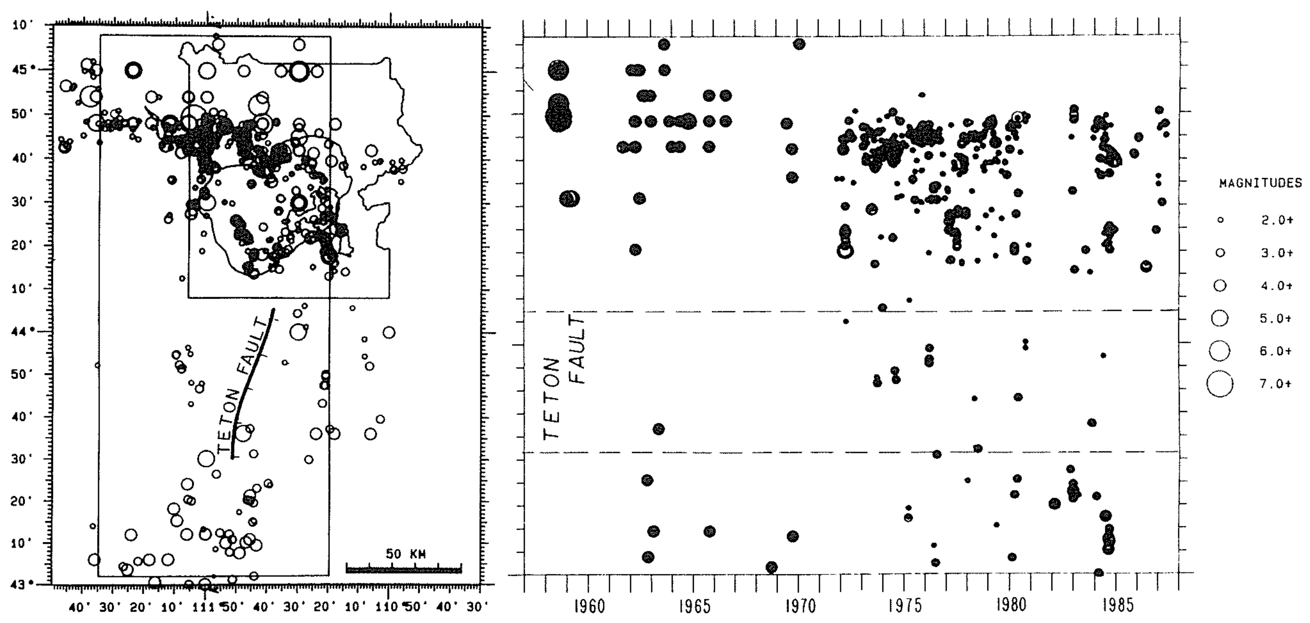


Figure 8. Space-time distribution of seismicity for the Teton region from 1959 to 1989 showing: (a) regional epicenter map, and (b) temporal distribution of corresponding earthquakes.

The Teton fault zone

The Quaternary expression of the Teton fault was first described on a general scale by Fryxell (1938a,b) and Horberg (1938), and the location of the fault was incorporated into the geologic maps of the Teton Range and the surrounding area by Love and Reed (1971) and Love and others (1972, 1992). **Figure 9** shows pictures of well-developed Quaternary fault scarps along the central part of the Teton fault. A detailed study of Quaternary faulting at specific locations along the Teton fault was made by Gilbert and others (1983) for an earthquake safety assessment of the Jackson Lake dam and included a map of the Quaternary trace of the Teton fault that was detailed at several specific locations.

Movement on the Teton fault may have begun as early as 13 Ma (Barnosky, 1984), although Love (1977) estimated movement on the fault began at 5 Ma based on the lack of coarse clastic detritus in the Miocene Teewinot Formation. Barnosky's interpretation was made on the basis of a 15° angular unconformity between the Miocene Colter Formation and the overlying Teewinot Formation exposed on the northeast side of Jackson Hole. Nonetheless, the Teton fault appears to have been generally influenced by the Basin and Range extensional tectonism that began earlier, ~17 to 20 Ma, in Utah and Nevada.

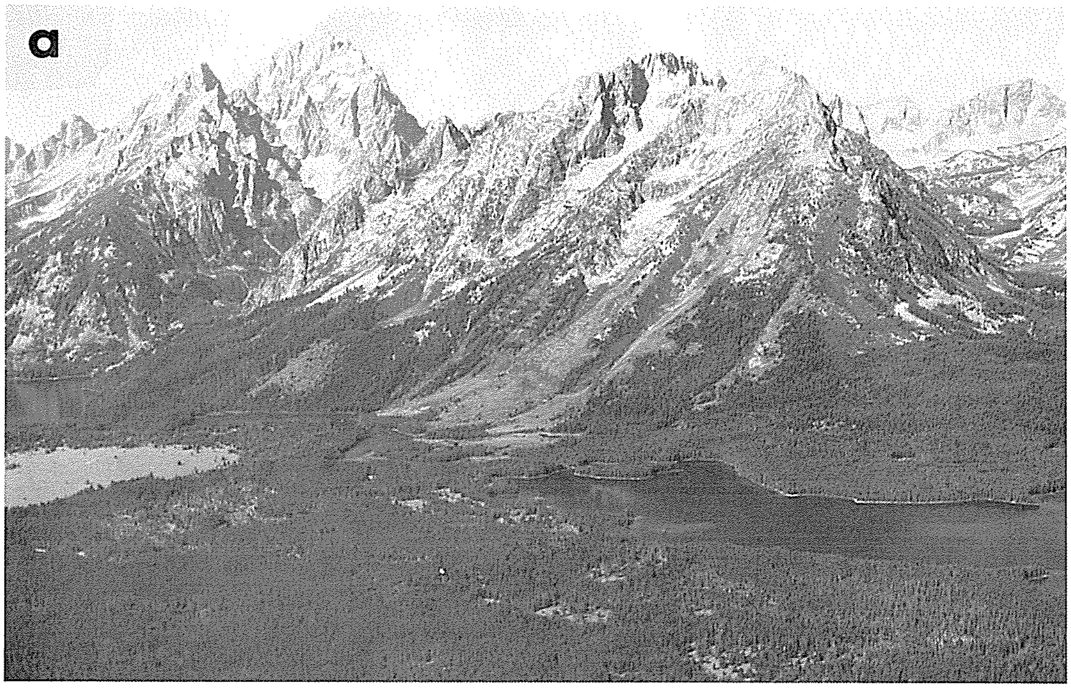
A number of interpretations of the magnitude of stratigraphic separation and geometry of the Teton fault have been proposed. Love and Reed (1971) and Love and others (1972) estimated a total stratigraphic separation ranging from 6 to 9 km (also see **Figure 6**). They implied that the Teton fault dips 70° to 80° east and is more than 90 km long, extending well beyond the southern end of the main topographic expression of the Teton Range. Tibbetts and others (1969) estimated that the Teton fault dips 30° east on the basis of seismic refraction measurements and gravity data. Lageson (1992) argued that the Teton fault terminates or ramps downward on a footwall ramp of the Cache Creek thrust. The geometry of Lageson's model implies that if the Teton fault is a planar, 45° to 60° dipping structure, it may occupy a north-striking ramp of the Cache Creek thrust or alternately, it may sole out into a listric geometry along the thrust. Unfortunately, none of these studies provide unequivocal information on the subsurface geometry of the fault.

Quaternary fault mapping

Expanding upon the work of previous investigators (e.g., Gilbert and others, 1983), we (D.D.S. and J.O.D.B.) have mapped the Quaternary scarps of the Teton fault at a scale of 1:9,000, extending from Phillips Canyon on the south to Steamboat Mountain on the north (**Figure 3**). Preliminary versions of the fault map were presented by Susong and others (1987) and Smith and others (1990a,b) and form the basis for the large-scale map of the Teton fault shown in **Sheet 1** (Smith, Byrd, and Susong, map pocket). The Quaternary expression of the Teton fault was delineated based upon identification of fault scarps that offset Pinedale glacial deposits, younger fluvial and alluvial deposits, and related neotectonic features. The detailed distribution and characteristics of glacial, alluvial, fluvial, and colluvial deposits adjacent to the fault were not mapped, except in special study areas discussed in the next section.

Quaternary fault scarps, from 3 m to 50 m high, are exposed for 41 km along the 55 km length of the Teton fault. The discontinuity in fault scarps, accounting for the 14 km deficit, is from the lack of identifiable exposures of faulting in areas of steep topography, lakes, and landslides. The Quaternary scarps define a prevalent N10°E strike along most of the fault and a down-to-the-east, normal sense of displacement (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). A distinct right-stepping, en echelon pattern characterizes the distribution of scarps in the central and southern sections of the Teton fault, whereas a linear pattern parallel to the topography of the range-front characterizes the northern part of the fault.

Bathymetric maps of Jackson Lake (Hayden, 1969) were examined for possible lake-bottom scarps but none were clearly observed. Some slope breaks were identified in the bathymetry data in Jenny and Leigh lakes that may represent fault scarps. Divers from the U.S. Bureau of Reclamation (J. Gilbert, personal communication, 1987) identified submerged trees beneath the west side of Jenny Lake, originally suggested as evidence for a recent large displacement on the Teton fault, but now thought to be a submerged landslide. They also identified a small topographic scarp near the west shore of the lake that



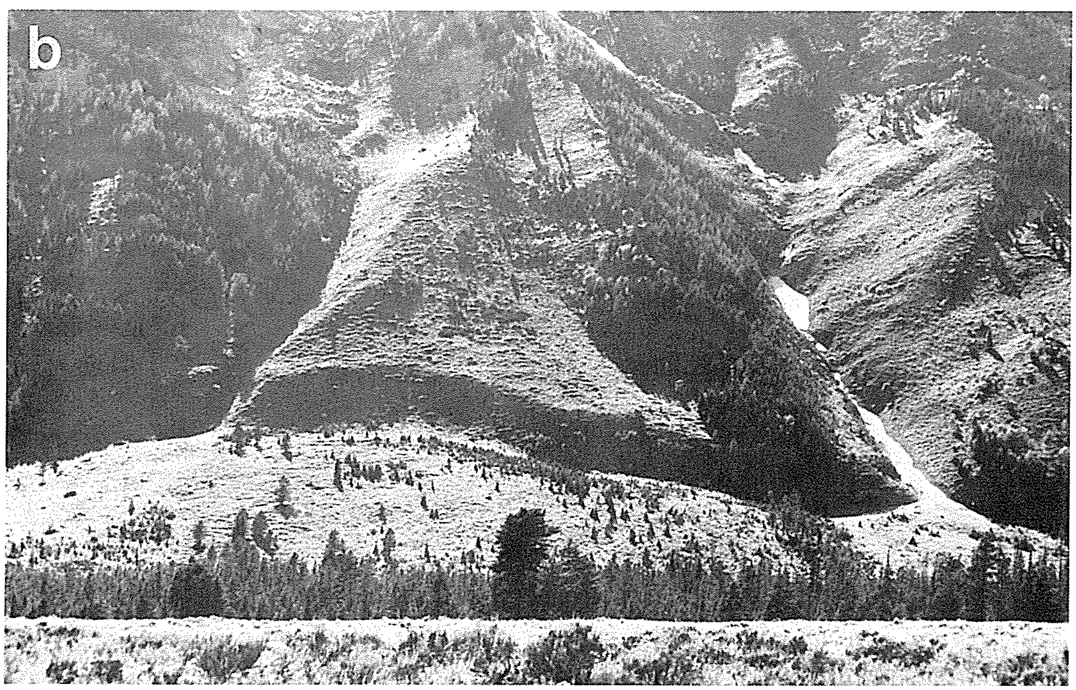


Figure 9. Pictures of post-glacial fault scarps of the Teton fault: (a) aerial view of the scarp west of String Lake between Jenny Lake (left) and Leigh Lake (right side) looking toward the Grand Teton (scarp is near the center of the photo), and (b) closeup view of the String Lake post-glacial fault scarp taken from the Cathedral Group scenic turnout. The String Lake scarp has a height of 34 to 50 m, which corresponds to a surface offset of 22 to 27 m. (Photo 9a by Robert B. Smith, 9b by Don Cushman of the National Park Service.)

corroborates our identification of the fault in that area.

In the central part of the Teton fault, near Taggart Lake, the fault bends approximately 24° clockwise (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). In this area, offset moraine crests suggest a left-lateral oblique separation of 8 to 26 m. The inferred strike-slip component may account for up to 50% of the slip on the fault in this area. This apparent horizontal displacement may be due to the interaction between the northeast strike of the fault and a predominant east-west sense of dip slip (Ostenaa, 1988). However, it should be noted that the evidence for lateral offset is equivocal given the complex geometry of intersecting nested glacial moraines that obscure the correlation of these features across the fault. We also note the lack of evidence for similar horizontal displacements on the southernmost and northern parts of the fault, where similar glacial features are offset vertically.

Previous workers (Behrendt and others, 1968; Tibbetts and others, 1969; Gilbert and others, 1983) concluded that a splay of the Teton fault extended beneath the west side of Jackson Lake. However, seismic reflection profiles along the west side of Jackson Lake and across Moran Bay (Smith, Pierce, and Wold, this volume) revealed no evidence of significant displacement of Quaternary sediments. This suggests that the scarps we have mapped along the range front west of the lake shore represent the most recent rupture(s) in this area. An alternative explanation may be that the recent faults are not preserved in the incompetent lake-bottom sediments, precluding their identification in the seismic profiles.

Near Steamboat Mountain, north of Jackson Lake, the Teton fault splays into a series of north-northeast-striking faults (**Sheet 1**, Smith, Byrd, and Susong, map pocket). These smaller and discontinuous faults offset Pinedale glacial deposits and the 2.0 Ma Huckleberry Ridge Tuff with both a down-to-the-west and a down-to-the-east sense of offset (**Sheet 1**, Smith, Byrd, and Susong, map pocket). This pattern of fault bifurcation, along with the decreasing magnitude of stratigraphic displacement across the northern end of the Teton fault, suggests that overall displacement is distributed northward onto multiple, right-stepping faults. A possible manifestation of this can be seen in the northeast-stepping pattern of Quaternary normal faults that extend into the southern Yellowstone Plateau (**Figure 2**; Locke and others, 1992).

On the basis of our mapping, the well-preserved, large Quaternary fault scarps at the south end of the Teton fault extend to the vicinity of Phillips Canyon and terminate north of the east-west-striking, Laramide Cache Creek and Jackson thrusts at the south end of the Teton Range (**Figures 2, 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). The Teton fault has been postulated to extend south of the town of Wilson by J.D. Love (personal communication, 1988) and Love and others (1992). However, we could not find unequivocal evidence for large Quaternary faults in this area on the basis of reconnaissance mapping. Thus, if the Quaternary expression of the fault extends south of Phillips Canyon, the recent scarps have either been eroded, or the Quaternary displacement on the Teton fault is obscured by river and stream terraces and is not as prominent here as it is observed to the north.

Detailed study areas

We constructed detailed topographic and geologic maps and fault scarp profiles at several locations along the Teton fault using an electronic distance measuring device (EDM) to measure the amount of Quaternary fault offset, scarp morphology, and scarp height. The EDM resolves the height and distance of individual points with a precision of 1 or 2 cm. Locations of these detailed study areas are shown on **Sheet 1** (Smith, Byrd, and Susong, map pocket).

Stewart Draw and Avalanche Canyon

Excellent Quaternary exposures of the Teton fault with an apparent left-lateral component of slip are present at the bottom of Stewart Draw and at the mouth of Avalanche Canyon south of Taggart Lake. At Stewart Draw (**Figure 10**), the Teton fault displaces a moraine crest with up to 26 m of left-lateral and 32 m of vertical slip. An antithetic fault scarp with a 2 m offset marks the east side of a back-tilted graben that extends some hundreds of meters north and south from this location (located off the map in **Figure 10**).

A similar fault geometry was observed at the Avalanche Canyon site (**Figure 11**) where the fault

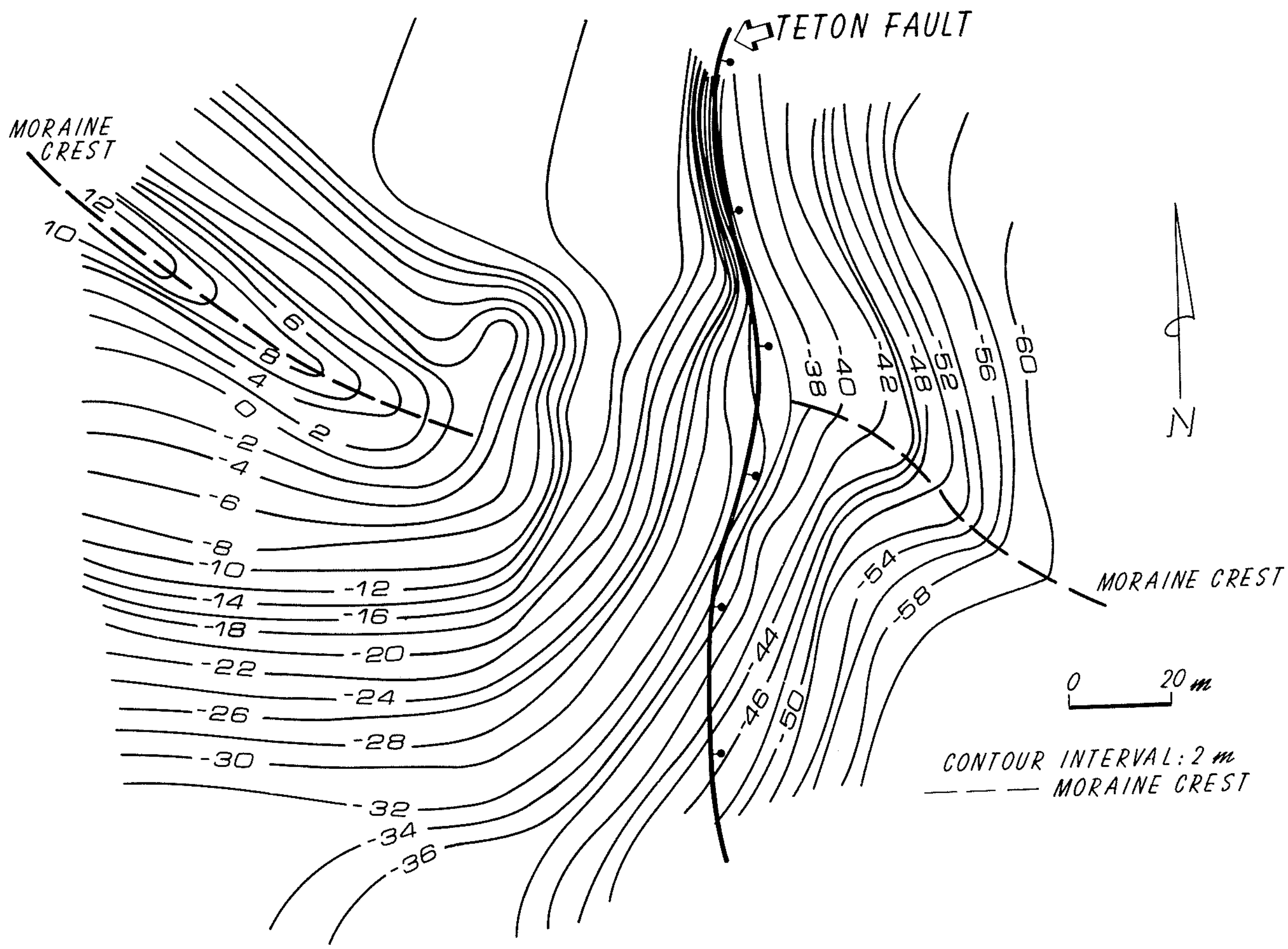


Figure 10. Topographic map of the Teton fault scarp on the south side of Stewart Draw. Location of study site is shown on Sheet 1 (Smith, Byrd, and Susong, map pocket). The Teton fault is shown as a heavy line with downthrown (with ball and bar) block to the east. Left-lateral displacement of 26 m is based on extrapolation of the moraine crest on the upthrown block into the fault trace. Data acquired in 1987 using an EDM.

offsets a moraine crest 8 m vertically and 9 m left-laterally. The two components of displacement suggest a total of 42 m of left-lateral oblique displacement at Stewart Draw, and 12 m at Avalanche Canyon.

We note, however, that the apparent left-lateral displacements exposed in glacial moraines at these locations can be amplified by the geometry of the fault scarps relative to the slopes of the moraine. For example, a component of left-lateral oblique displacement of an east-west trending moraine will produce apparently larger displacements on the north side of the moraine crest and smaller displacements on the south side. For this reason, the scarps appear to be relatively small, 0 to 2 m, on the north (right) side of the Avalanche Canyon lateral moraine. On the south (left) side, scarp heights are as large as 10+ m. As a result, care was exercised in estimating the total Quaternary tectonic offset in these areas of coalescing glacial and topographic features.

Jenny Lake

The Quaternary trace of the Teton fault changes from N10°E, 1 km south of Jenny Lake, to N50°E where it cuts the Pinedale-aged lateral moraine (**Figure 12**). The moraine crest is offset approximately 16 m vertically across the fault. The fault trace turns back to a N10°E strike about 1/2 km north, where it intersects the west shore of Jenny Lake (**Sheet 1**, Smith, Byrd, and Susong, map pocket). This relatively abrupt change in fault strike corresponds to a 350 m eastward step in the fault trace that also coin-

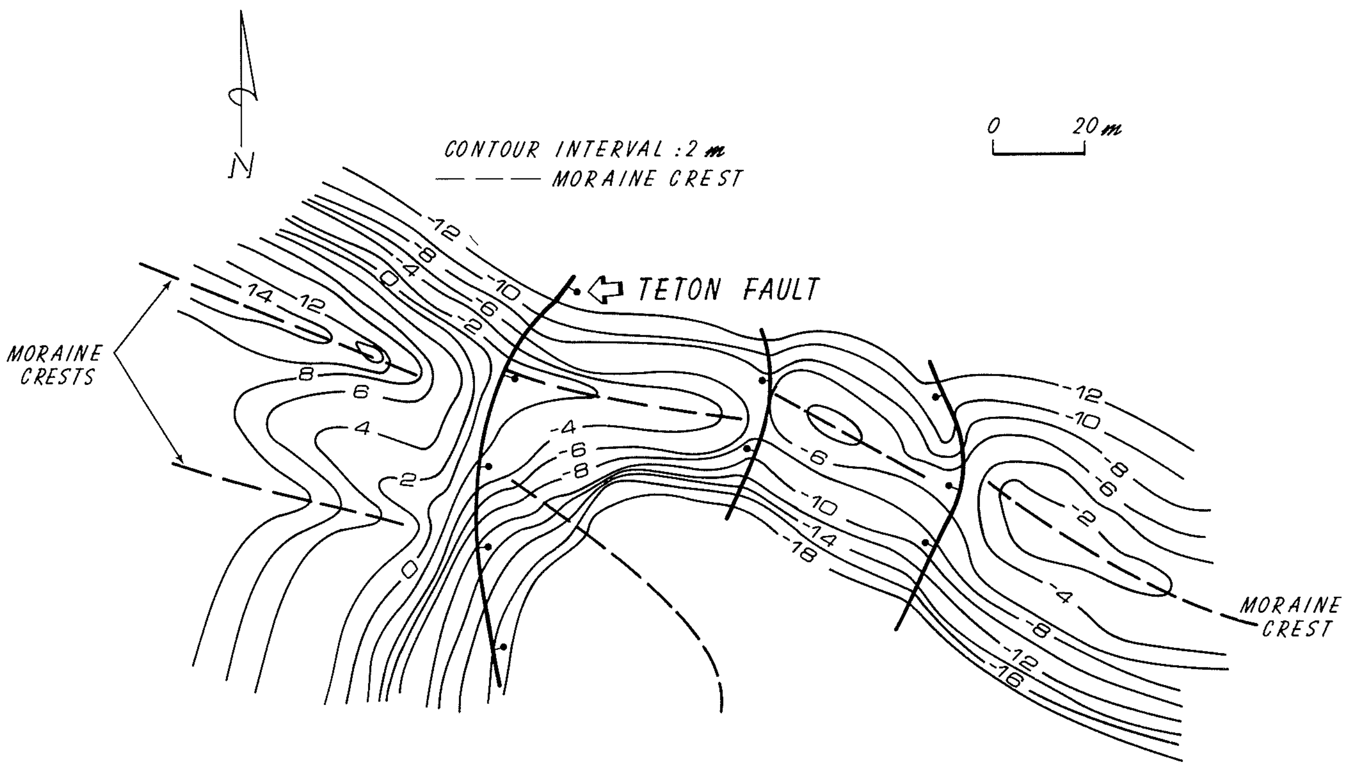


Figure 11. Topographic map of the Teton fault scarp on the south side of the mouth of Avalanche Canyon. Location of study site is shown on Sheet 1 (Smith, Byrd, and Susong, map pocket). Teton fault and antithetic fault are shown in heavy line with ball and bar on downthrown block. Interpreted left-lateral displacement of 9 m is based on extrapolation of the trace of the moraine crests on the upthrown block into the fault trace. Data acquired in 1987 using an EDM.

cides with a marked increase in the thickness of surficial glacial deposits. Extrapolation of a predominantly east-west-trending normal-slip vector onto the fault implies a left-lateral sense-of-slip for the N 50° E striking portion of the fault. Unfortunately, the complex anastomosing pattern of nested moraines precludes an unequivocal identification of horizontal displacement in the south Jenny Lake moraine.

Lateral variations of scarp height and offset

Seventeen elevation profiles of Quaternary scarps along the Teton fault were surveyed with an EDM to determine scarp heights and surface offsets. Geologists of the U.S. Bureau of Reclamation (Gilbert, and others, 1983) measured eight additional scarp profiles using a Jacobs staff and inclinometer. These data are summarized in **Table 1** with profile locations shown on **Sheet 1** (Smith, Byrd, and Susong, map pocket).

Scarp profile locations were selected to evaluate sites representative of Quaternary faulting. Fault scarps modified by slumping or gullies were not profiled. Surface deposits along the profiles consisted of glacial till, alluvium, and colluvium with sand- to boulder-sized clasts. Measured scarp-slope angles range from 14° to 40° with the steeper slopes at or near the angle of repose for the bouldery deposits.

In our analysis of the fault scarp profiles, we employed the definitions of scarp height and surface offset by Bucknam and Anderson (1979). Scarp height is defined as the vertical height of the scarp measured from the toe to the top of the scarp. Surface offset is generally defined as the vertical offset across the fault between the tectonically undeformed footwall and hanging-wall slopes (**Figure 13**), but we modified the definition to be the measured offset determined by projecting the hanging-wall slope to the top of the scarp. In the absence of trench data, the

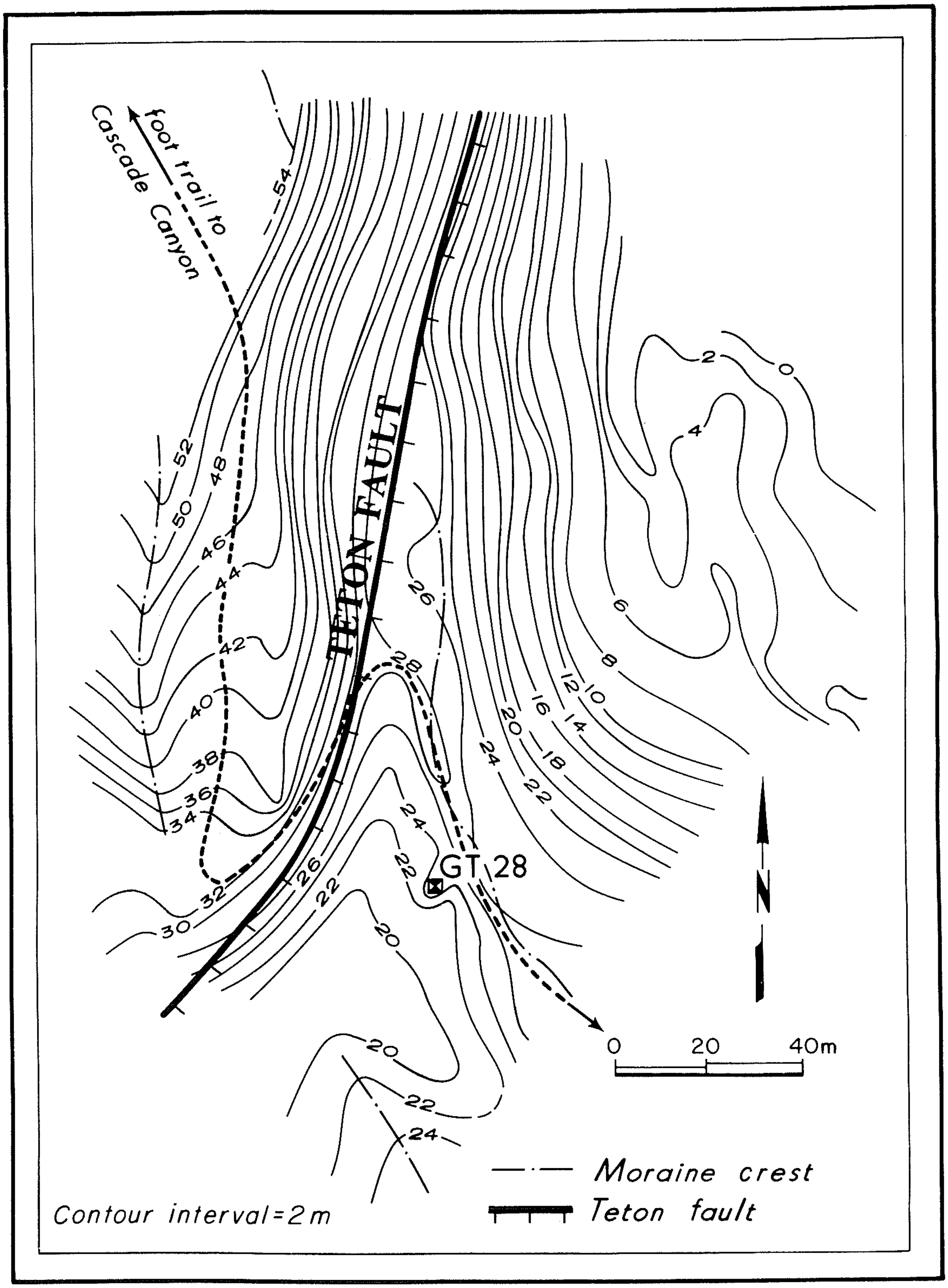


Figure 12. Topographic map of the Teton fault at the south Jenny Lake moraine. Location of study site is shown on Sheet 1 (Smith, Byrd, and Susong,map pocket). Teton fault is shown in heavy line with hachures, downthrown block is to the east. Data acquired in 1989 using an EDM. GT28 corresponds to a leveling benchmark in Figure 19.

surface offset is considered the best measure of the fault slip since it does not include the apparent displacement due to rotation of the footwall or hanging-wall surface into the fault. Calculation of surface offset assumes that the footwall and hanging-wall slopes were continuous prior to faulting, or that the slope angles were known prior to the most recent ground-rupturing event. If surficial deposits are moved from the footwall to the hanging wall and no erosion takes place in the hanging wall adjacent to the original fault scarp, then the scarp degradation effectively decreases the amount of tectonic displacement that can be measured in the field. As a result, our estimates of tectonic displacement from surface offset data are considered to define the minimum.

Measured Quaternary scarp heights along the Teton fault (**Figure 14**) range from 3.6 m to 50 m and surface offsets range from 3 m to 28 m (**Table 1**). Based on these data, the average surface offset appears to increase from 10 to 13 m (18.6 m maximum) in the southern section of the fault to about 20 m (28.4 m maximum) in the middle section (**Figure 14**). Insufficient data preclude estimation of average surface offsets for the northern part of the fault.

The south-to-north variations in Quaternary surface offset along the Teton fault generally coincide with lateral variations in average topographic relief along the crest of the Teton Range (**Figure 14**) and suggest a causal relationship between the areas of

Table 1. Morphologic properties of Quaternary scarps of the Teton fault. Scarp topography determined by EDM for our study and by hand level for the results of Gilbert and others (1983). Profile number corresponds to profile locations on Sheet 1.

Profile name	No.	Scarp height (m)[1]	Surface offset (m)[2]	Surface offset (m)[3]	Scarp slope angle (°)[1]
			Southern segment		
Granite Canyon	trench	3.6	3.0		14 - 21
Granite Canyon	11	12.7 - 14.0	10.9- 12.6		15 - 35
Granite Canyon	12	10.4 - 11.0	9.8 - 10.1	11.3	25 - 36
Teton Village	13	12.2 - 48.5	10.8 - 18.6	7.3- 7.9	28 - 35
Teton Village	14	26 - 36	13.6 - 15.5		28 - 35
Average			**13**		
			Middle segment		
Lupine Meadows	1	19 - 25	13.0 - 19.3	>10.7	32 - 38
Lupine Meadows	2	25.0	18.4 - 25.4		30 - 38
Burned Wagon Gulch	3	9.2 - 12.4	7.6 - 9.3		26 - 29
Avalanche Canyon	—	5.2 - 7.9		5.2- 7.0	26 - 27
Bradley Lake	4	15.0	9.2 - 14.0		25 - 34
Bradley Lake	5	11.3 -14	10.7 - 11.2		16 - 34
Taggart Lake	6	22.0	17.5 -19.4		25 - 38
Taggart Lake	7	17.3 - 22	11.0 - 13.0	11.6	19 - 30
Taggart Lake	8	12 - 29	12.5 - 14.8	12.2	24 - 33
Beaver Creek	9	17.0 - 22	8.7 - 12.9		30
String Lake	10	34.4 - 50.0	22.0 - 26.6	19.2	27 - 40
Trapper Lake	15	30.2 - 47.8	23.4 -28.4	23.8[1]	26 - 32
Moran Bay	17	14.0 - 14.5	10.3 - 11.9		31 - 33
Average			**15**		
			Northern segment		
Colter Canyon	16	20.8	11.0 - 18.2		22 - 29
Wilcox Point	Estim.	4.5 - 12.0			

[1]Range of values reflects data from this study and that of Gilbert and others (1983).
[2]Surface offsets were calculated by projecting the hanging-wall slope to the top of the scarp.
[3]Data from Gilbert and others (1983).

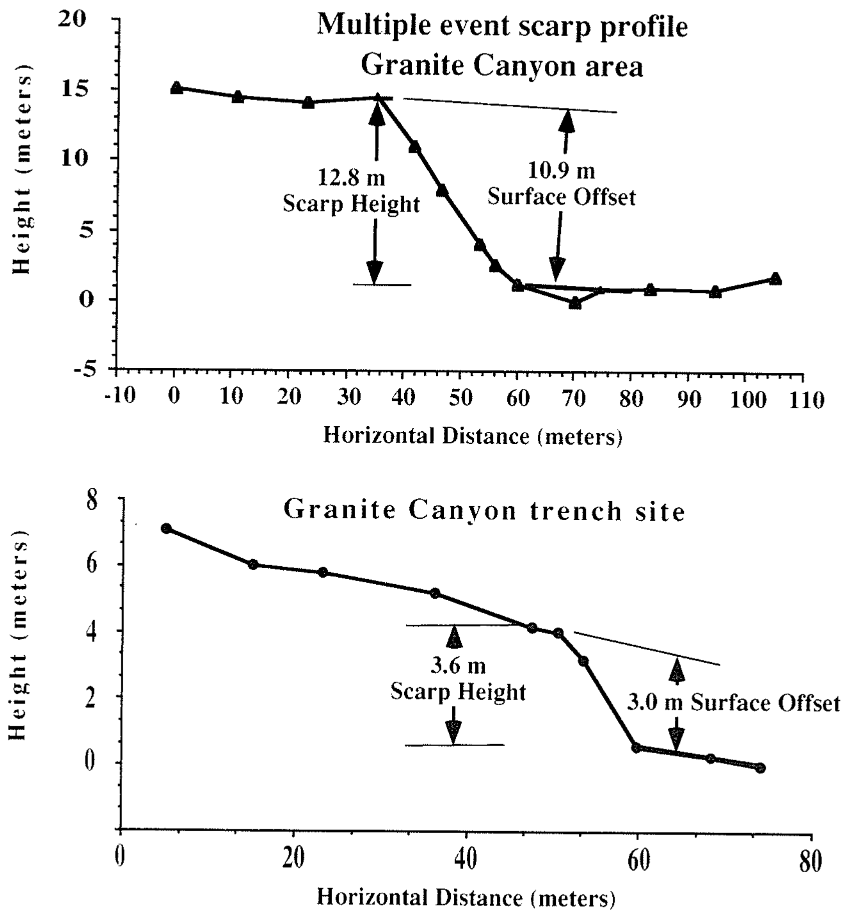


Figure 13. Topographic profiles of Quaternary fault scarps at the mouth of Granite Canyon: (a) multiple-event scarp approximately 120 m north of the trench site; and (b) scarp profile at the trench site.

highest topography and the areas of greatest Quaternary fault displacement. Fryxell (1938a) first noted that the area of highest topographic relief along the central part of the Teton Range does not coincide directly with the north-south-trending drainage boundary of the range. It is displaced approximately 3 to 4 km east of the drainage divide where it is marked by the highest peaks, e.g., Grand Teton, South and Middle Tetons, Mt. Moran, etc. (**Sheet 1**, Smith, Byrd, and Susong, map pocket). This systematic, eastward uplift of the highest topography of the Teton Range is consistent with concomitant uplift and westward tilt of the range at rates that exceed those of erosion.

Fault segmentation

Correlation of surface ruptures associated with a single earthquake and individual segments of normal faults forms the basis for the "characteristic earthquake model" proposed by Schwartz and Coppersmith (1984). Therefore, identification of individual fault segments can provide a general guideline for evaluating the seismogenic capacity of a fault zone. Schwartz and Coppersmith (1984) and Machette and others (1991) have suggested a number of criteria for identification of fault segmentation, such as extent of similar aged faulting, changes in fault trend, changes in range topography, lateral variations in fault strike and footwall structures, and

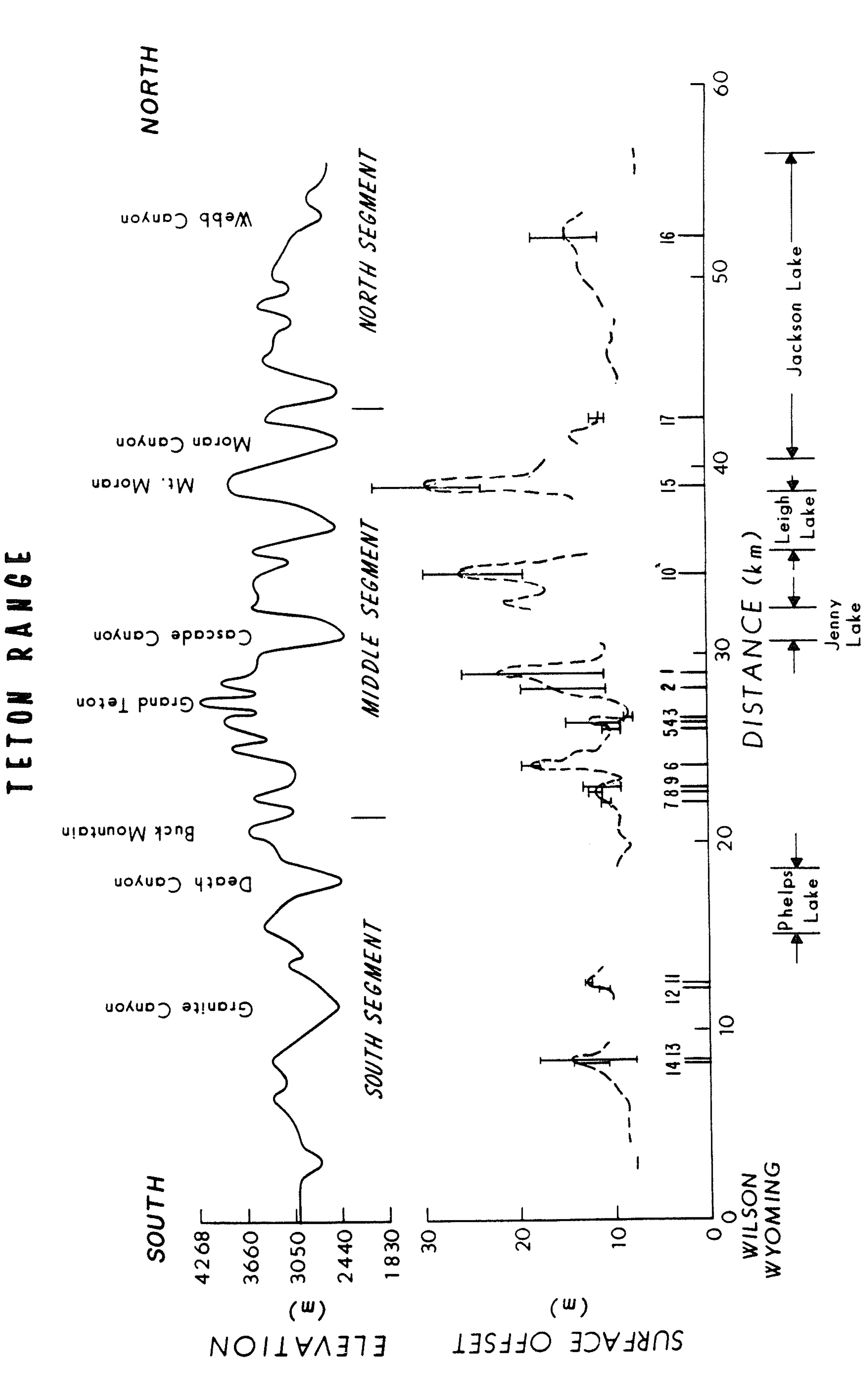


Figure 14. Lateral variation of Quaternary surface offsets of the Teton fault and averaged maximum elevation on the adjacent Teton Range. Vertical lines = locations of detailed scarp profiles. Numbers correspond to scarp profile locations shown on Sheet 1 (Smith, Byrd, and Susong, map pocket) and detailed information is given in Table 1. Fault offsets dashed where inferred.

variations in hanging-wall geometry interpreted from gravity anomalies. Using the above criteria, we suggest that the Quaternary expression of the Teton fault is made up of two and possibly three fault segments (**Figure 3**).

The southern segment begins 5 km south of Teton Village and extends north for approximately 20 km to the vicinity of Taggart Lake (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). The general strike of the southern segment is N20°E and the surface offsets averages 13 m. The highest topography in this area of the Teton Range is about 3,000 m. The identification of a separate middle segment is somewhat problematical. However, variations of surface offset, fault strike, footwall topography, and gravity anomalies in the hanging-wall block suggest that a separate segment extends about 22 km from Taggart Lake north to Moran Bay (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). This segment has the largest surface offsets and its boundary with the southern segment is marked by a change in strike from N24°E to almost north-south, north of Taggart Lake. The middle section of the Teton fault also corresponds to the area of highest topography of the Teton Range that ranges from 3,810 m to 4,200 m and averages ~ 3,500 m compared to < ~3,000 m to the north and south. We also note that the best evidence for a component of left-lateral displacement at Avalanche Canyon and Stewart Draw is in this area, but we cannot definitely attribute this observation to a kinematic property of the faulting.

The boundary between the southern and middle segments is further suggested by the location of the southern end of a large negative Bouguer gravity anomaly (**Figure 15**) located at the boundary between two alluvial-filled sedimentary basins beneath Jack-

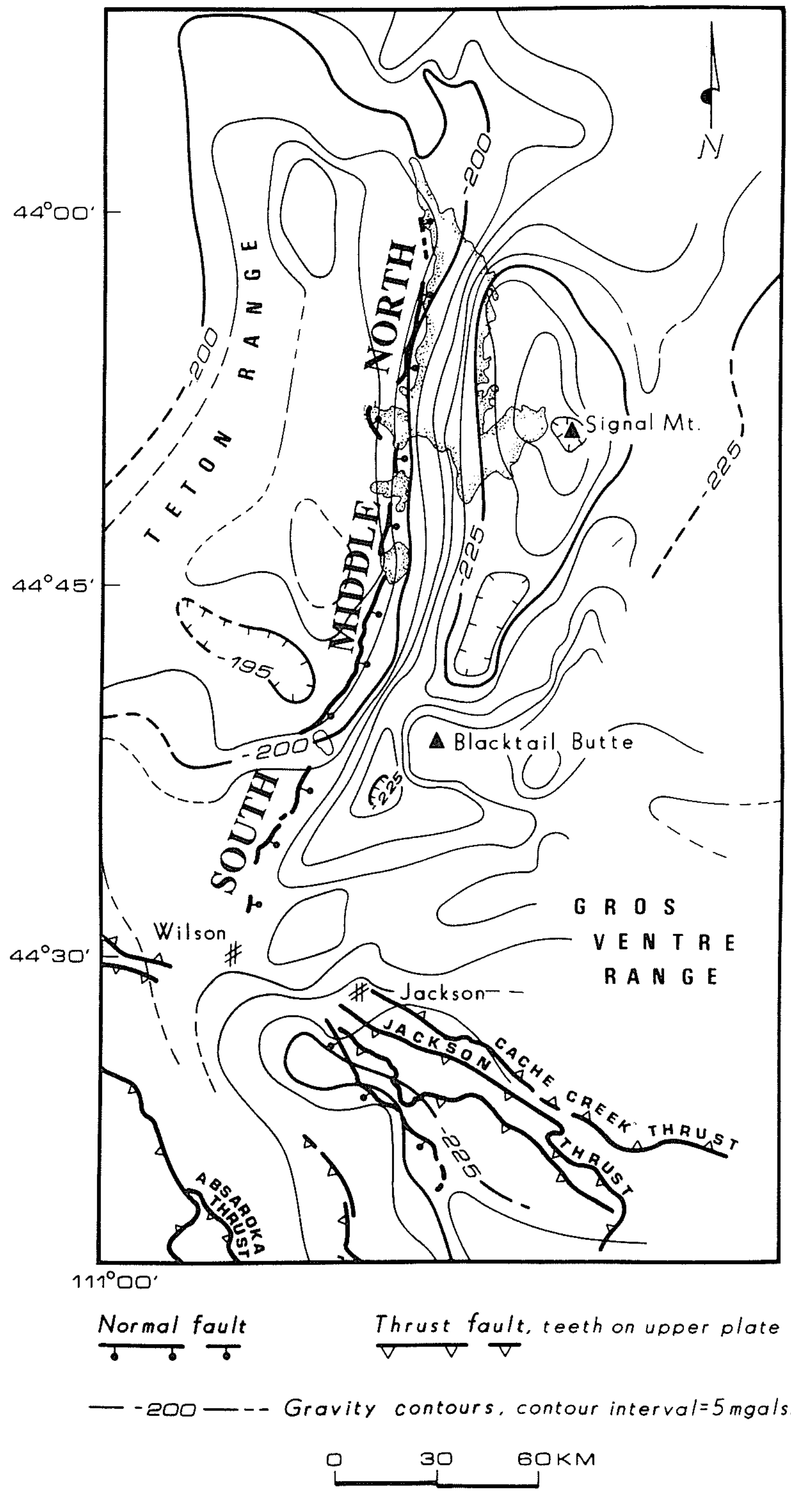


Figure 15. Complete Bouguer gravity map of the Jackson Hole region showing the Teton fault and proposed fault segments (gravity map modified from Behrendt and others, 1968).

son Hole (Behrendt and others, 1968). We ascribe the east-west gravity gradient to shallowing of high-density footwall basement rocks beneath the valley coincident with the eastward projection of the segment boundary.

On the basis of interpreted slip directions of the Teton fault, Ostenaa (1988) concluded that the change in fault strike and the presence of the gravity high in this area do not necessarily indicate the existence of a segment boundary. In his interpretation, the southern and middle segments represent a single, 42 km-long segment. This is a reasonable interpretation, especially if one considers that the 1.3- and 2.8-m most recent surface displacements (Byrd, 1991), such as those exposed in the Granite Canyon trench (discussed in a later section), generally correspond to surface ruptures that extend 30 km or more and are expected to be associated with magnitude 7+ earthquakes (Mason and Smith, 1990; de Polo and others, 1991).

The boundary between the northern and middle segments of the Teton fault (**Figure 3**) is located on the north side of Moran Bay where the middle segment terminates against Precambrian footwall rocks (also see **Sheet 1**, Smith, Byrd, and Susong, map pocket). The northern segment then steps 1.5 km eastward and extends 13 km northward from the north side of Moran Bay along the west side of Jackson Lake to Wilcox Point (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). North of Wilcox Point, the fault extends beneath the northernmost end of Jackson Lake and the Snake River delta, reemerging east of the lake as the series of N10°E striking faults in the Steamboat Mountain area. Other branches of the fault may extend north-northwest along the Snake River and the northern base of the Teton Range to the boundary of Yellowstone National Park. Evidence of surface displacements along these splays has not been identified by reconnaissance mapping of this area by the U.S. Bureau of Reclamation (Dean Ostenaa, personal communication, 1990).

The implication of the contrasting segmentation models, i.e., two versus three fault segments, is particularly important for assessing the expected size of future earthquakes on the Teton fault. As a result, we include both two- and three-segment models in subsequent discussions of future earthquakes.

Dating Quaternary displacements on the Teton fault

Preliminary results from trenching

Stratigraphic interpretation of trench exposures of active faults can provide definitive data on the age and magnitude of surface displacements and hence on the recurrence intervals of prehistoric earthquakes. To acquire this information, a small trench was excavated across a 3.6 m fault scarp at the mouth of Granite Canyon near the southern end of the Teton fault (see **Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket, for location). Details of the trench are not given here because this aspect is the focus of an on-going study. However, we summarize the initial findings from the trenching given by Byrd and Smith (1990a,b, 1991) and Byrd (1991).

The Granite Canyon trench exposed fluvial and debris flow deposits overlying Pinedale glacial till that were offset 4.1 m down-to-the-east on an 85°E dipping fault plane (Byrd and Smith, 1990b, 1991; Byrd, 1991). The estimated offset is based on correlation of fining-upward fluvial deposits capped by a 2 to 6 cm-thick floodplain deposit exposed in the hanging-wall and footwall blocks. Westward back tilt of ~ 3° was observed in the hanging-wall block, whereas units in the footwall block exhibited an average 2° east depositional slope. Subtracting the 5° of back tilt in the hanging-wall units yields a net tectonic displacement of 4 m.

Two charcoal samples collected from the base of the colluvial wedge overlying the floodplain deposit and from the base of the floodplain deposit yielded radiocarbon ages of 7,150 ± 120 years and 7,240 ± 190 years, respectively (Byrd and Smith, 1990a). We believe that these samples represent the same burn event due to the overlap of the standard deviations of calculated ages, the inferred rapid deposition of the floodplain deposit, and the 150-year to 250-year recurrence of major forest fires (Peter Hayden, personal communication, 1991) in this region. The average of the two samples is 7,175 ± 100 radiocarbon years and conversion of radiocarbon years to calendar years (Stuiver and Reimer, 1986) gives a calendar age of 7,980 ± 210 years (we refer to radiocarbon ages to be consistent with previous citations of the age of Pinedale glaciation by other workers). This averaged age represents the maximum calendar age for a single faulting event exposed in the trench.

We note from the recent analyses of Byrd and Smith (1990a,b) and Byrd (1991) that it is quite probable that the 4.1 m displacement is the product of two prehistoric slip events. If a younger event contributed to the displacement, the total tectonic displacement could be divided into a 2.8 m offset associated with the oldest, (7,175 year) event and 1.3 m offset accompanying a younger slip. Additional radiocarbon dating is being done to assess the ages of faulting for this Holocene, multiple-event scenario.

Dendochronological dating of the Teton fault

Attempts to determine the age of the most recent faulting on the Teton fault using dendochronologic techniques were made by Gordon Jacoby of Lamont Doherty Geological Observatory, Columbia University in 1987, who concluded that the oldest trees he sampled along or on the Quaternary scarps in the middle and southern parts of the Teton fault were about the same age (approximately 130 years old). We suspect that large forest fires between 1840 and 1890 (Loope and Gruell, 1973) destroyed most older trees along the Teton Range front, thereby precluding the use of dendochronology to estimate the age of faulting before that time.

Slip rates and earthquake recurrence intervals for the Teton fault

Comparison of long-term rates of displacement with point samples of single or multiple prehistoric earthquakes can often be misleading. Large errors in the magnitude of displacement and time intervals, short-term fluctuations from an "average rate", and a lack of multiple prehistoric events can contribute to misinterpretations of short-term versus long-term deformation rates. As a result, comparisons of long-term (13 to 9 Ma), Quaternary (2 Ma), and post-glacial (14 ka) displacement rates should be made with caution, especially with regard to evaluating the contemporary earthquake capability of the fault.

Estimates of post-glacial displacement rates are based on a single slip-event scenario at the Granite Creek trench and an extrapolation of the surface offset to the multiple-event, 12.8 m-high fault scarps (**Figure 13**) exposed in Pinedale glacial deposits 120 m to the north. As a result, these are estimates of post-glacial surface offset rates and should be considered as conservative. A 3 m surface offset is associated with the 3.6 m scarp at the Granite Canyon site (**Figure 13**). Subtracting this surface offset from the 10.9 m offset on the larger scarps, and assuming a 14,000 year age for the cessation of Pinedale glaciation (Porter and others, 1983), results in an average 1.6 mm/yr surface-offset rate and an estimated recurrence interval of 1,650 years (**Figure 16**). This estimate assumes the 7,175 ± 100-year event is the youngest on this portion of the fault and the displacement and surface offset is the same at the trench site as on the adjacent larger scarps. However, for the Holocene two-event scenario, the younger but undated slip event will decrease the 14,000 to 7,175 yr surface offset rate (Byrd and Smith, 1990b). A lower slip rate is implied if one assumes an average of 30,000 years for the end of Pinedale glaciation (Pierce and others, 1976). In this scenario, a lower slip rate of 0.45 mm/yr is implied with a recurrence interval of approximation 6,000 years for four equivalent M_S= 7+ postulated events (**Figure 16**).

Estimates of Quaternary displacement rates for the Teton fault were also made on the basis of a projection of the 2.0 Ma old Huckleberry Ridge Tuff into the postulated location of the fault (Gilbert and others, 1983; Smith, Pierce, and Wold, this volume). Gilbert and others (1983) compared the elevations of the westward-dipping exposures of the Huckleberry Ridge Tuff exposed on Signal Mountain, 12 km east of the Teton fault (**Figure 4**), to the highest elevation of the tuff on the west side of the Teton Range and proposed a 2.8 km offset. Smith, Pierce, and Wold (this volume) and Gilbert and others (1983) projected the location of the Huckleberry Ridge Tuff from exposures east and north of Jackson Lake to suggest an estimated offset of 2.5 ± 0.4 km. The average Quaternary displacement rates corresponding to these projected offsets are estimated in the range of 1.0 to 1.4 mm/yr (**Figure 16**). However, the magnitude of

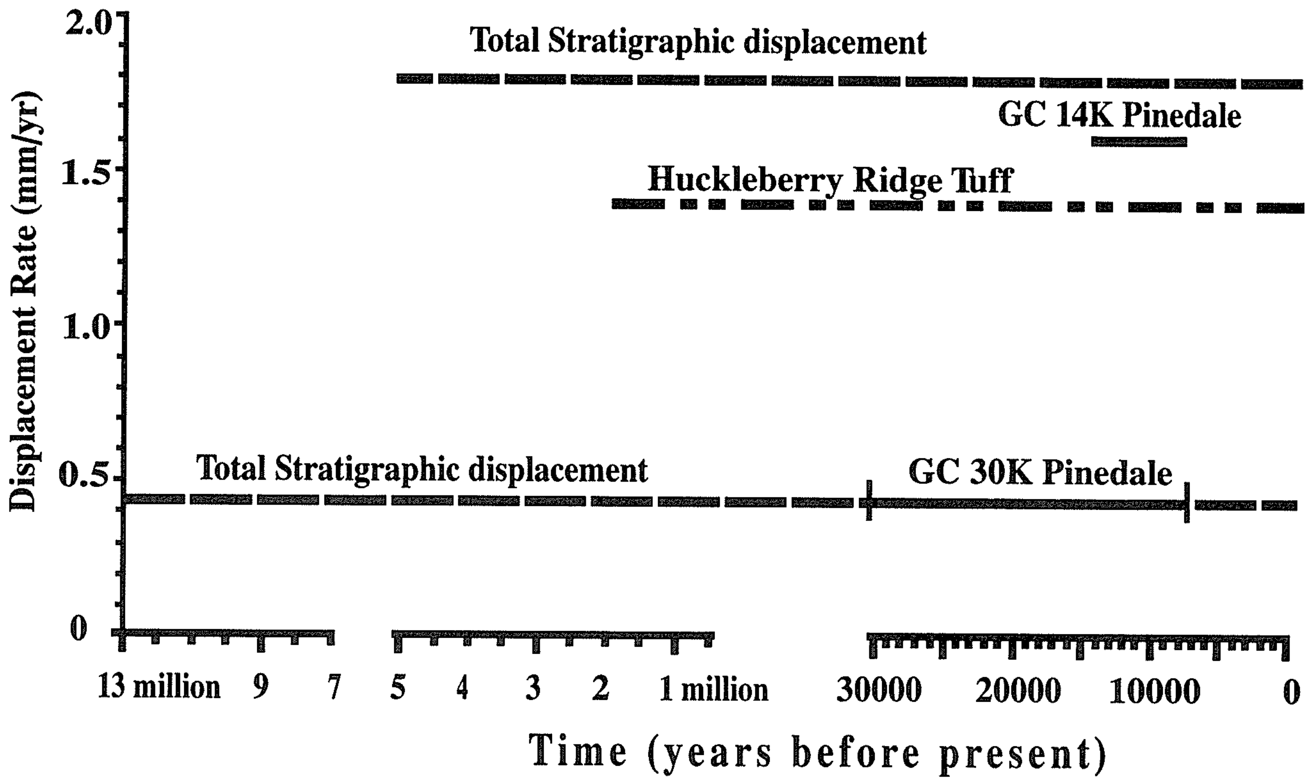


Figure 16. Estimated displacement rates for the Teton fault. The two different total stratigraphic displacement rates reflect maximum and minimum estimates based on 5 Ma (Love, 1977) to 13 Ma (Barnosky, 1984) and 6 km to 9 km stratigraphic separation across the Teton fault. Huckleberry Ridge Tuff rates are from Gilbert and others (1983) and Smith and others (this volume). GC 14K Pinedale (14 ka) and GC 30K Pinedale (30 ka) are youngest and oldest ages of glacial deposits and a single faulting event resulting in 4.0 m surface offset at Granite Canyon trench site.

westward tilting of Signal Mountain caused by possible movement on a small normal fault east of Signal Mountain (Gilbert and others, 1983) is not known or included in these estimates; therefore, the offsets and resulting displacement rates are considered maximum values.

Initial estimates of recurrence intervals for large $7.0 < M_S < 7.5$ earthquakes on the Teton fault were made by Gilbert and others (1983), who suggested a range from 700 to 2,000 years with an average interval of 1,400 years. These estimates were based on comparisons of measured surface offsets on the Teton fault with observations from historic earthquakes in the Intermountain region. Doser and Smith (1983) estimated a recurrence interval of 800 to 1,800 years for an $M_S = 7.5$ event on the Teton fault using the summation of seismic moments of historical earthquakes. These estimates span the 1,650-year return rate suggested from our trenching study.

If one extrapolates the 0.45-mm/yr and 1.6-mm/yr slip rates from 7,175 ± 100 years to the present, then the southern segment of the Teton fault has accumulated a "slip deficit" from 3.2 m to 14 m, respectively. The lower estimate of a 0.45-mm/yr slip rate implies that the Teton fault may be accumulating stress at a "normal rate" because the 3.2-m slip deficit is comparable to the surface displacements accompanying M_S =7.2+ normal-faulting earthquakes (Bonilla and others, 1984; Mason and Smith, 1990; de Polo and others, 1991). The higher 1.6-mm/yr slip rate suggests that the southern part of the fault has already stored sufficient energy for an $M_S \sim 7.2+$ earthquake. An earthquake of this magnitude, however, would rupture most if not all the Quaternary trace of the Teton fault. Note that there is no other information on Holocene slip rates for the middle and northern segments of the fault, thus precluding a definitive determination of the Holocene slip rates and recurrence intervals for the entire Teton fault.

Ground deformation associated with the Teton fault

Subsidence and asymmetric tilt of the hanging-wall block is a significant component of the co-seismic ground deformation associated with large, scarp-forming normal-faulting earthquakes (**Figure 17**). These phenomena have been observed with three historic earthquakes: (1) M_S=6.8 Dixie Valley, Nevada (Slemmons, 1957; Snay and others, 1985); (2) M_S=7.3, Borah Peak, Idaho (Stein and Barrientos, 1985); and (3) M_S=7.5, Hebgen Lake, Montana (Myers and Hamilton, 1964; Savage and Hastie, 1966). These large normal-faulting earthquakes demonstrated relatively small (generally less than 15%) footwall uplift compared to substantial hanging-wall subsidence and asymmetric tilt of adjacent valleys (**Figure 17**).

Co-seismic ground deformation associated with normal faulting has also been modeled theoretically by King and others (1988). In their boundary-element model, a 45°-dipping normal fault was simulated in a 16 km-thick elastic half-space with an underlying fluid layer (**Figure 18**) and 1 m dip-slip displacement along the entire fault corresponding to an M_S = 7.1 earthquake. The results of King and others (1988) modeling show that the theoretical ratio of hanging-wall subsidence to footwall uplift is about 4:1, which is similar to that observed with large historic normal-faulting earthquakes (**Figure 17**). If this ratio is typical for large normal faults, then we can assume that deformations accompanying prehistoric earthquakes along the Teton fault have had a greater component of hanging-wall valley subsidence than footwall uplift.

In southern Jackson Hole, an area of anomalous down-to-the west tilt and subsidence of the ground

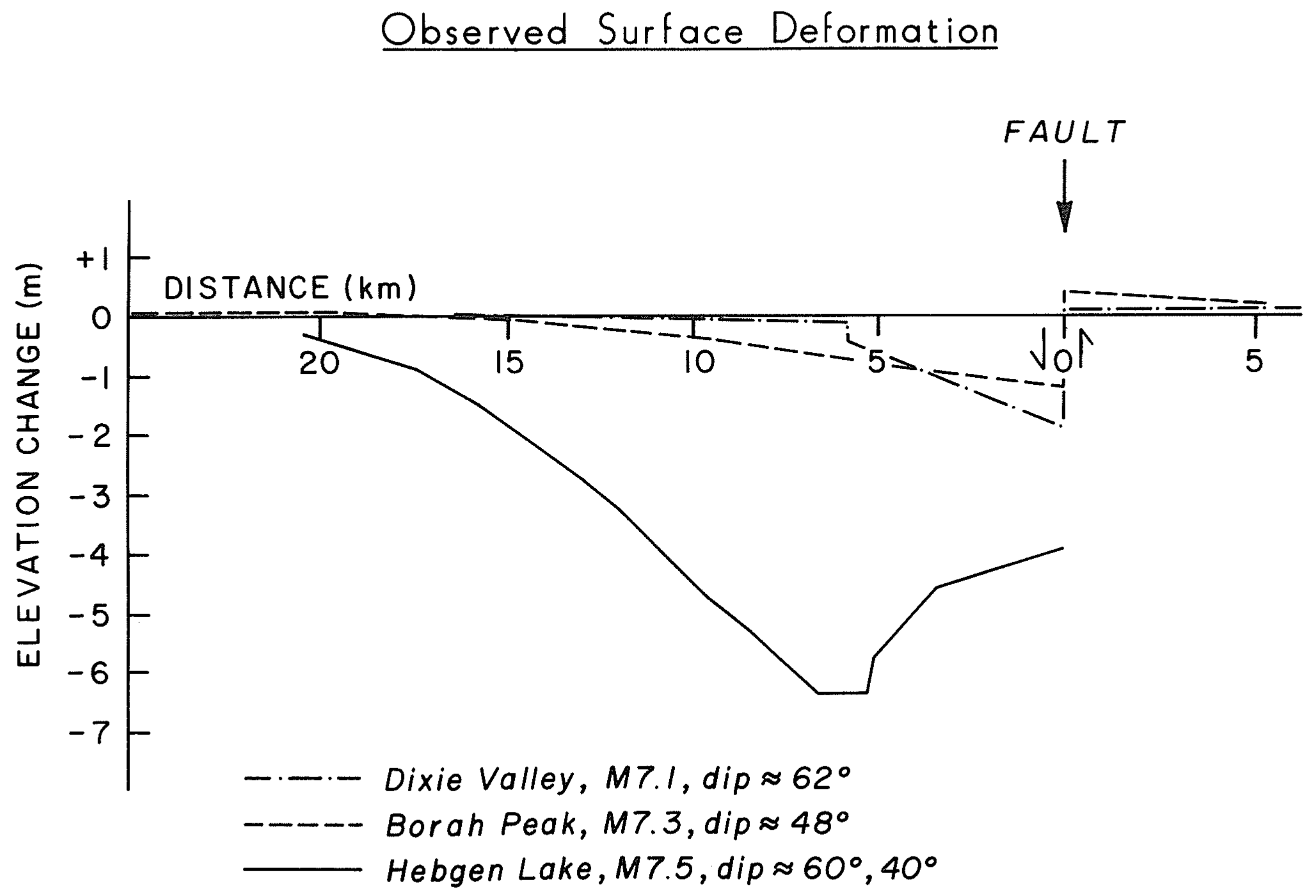


Figure 17. Co-seismic, vertical ground deformation accompanying three large, scarp-forming Basin and Range province earthquakes: (1) M_S = 6.8, 1954, Dixie Valley, Nevada (Slemmons, 1957; Snay and others, 1985); (2) M_S = 7.5, 1959, Hebgen Lake, Montana (Savage and Hastie, 1966); and (3) M_S = 7.3, 1983, Borah Peak, Idaho (Stein and Barrientos, 1985).

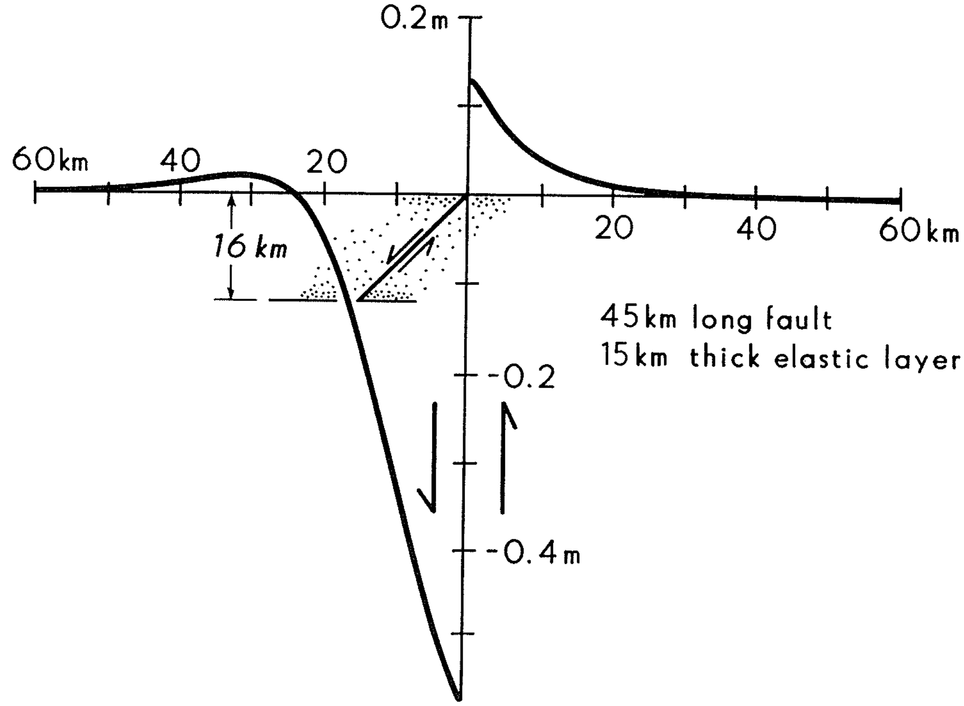


Figure 18. Theoretical ground deformation produced by a large, normal-faulting earthquake from boundary element modeling of the free surface, assuming a co-seismic displacement of 1 m on a 45°-dipping normal fault (from King and others, 1988).

surface (**Figure 19**) was reported by Love and Montagne (1956) and is similar to that shown in **Figures 17** and **18**. Using an altimeter to measure elevations, they documented this unusual topography extending from the Teton fault a few kilometers eastward across the valley floor (**Figure 19**). Their topographic profiles were constructed beginning on the north from Lupine Meadows, extending south to the vicinity of the town of Wilson (general location shown on **Figure 3**). While altimetry is not as precise as geodetic leveling, it is usually accurate to a few meters over tens of kilometers of profile length and is considered sufficiently accurate to resolve large-scale variations in height. It should be noted that Love and Montagne (1956) postulated prehistoric earthquakes accounted for this anomalous pattern of ground deformation. Their observations were made several years before the general style of hanging-wall subsidence associated with normal faulting was known as an important kinematic property of large, scarp-forming earthquakes in the Basin and Range province.

Streams emanating from the Teton Range would normally be expected to flow directly eastward to the Snake River (**Sheet 1**, Smith, Byrd, and Susong, map pocket). However, the topographic depression documented by Love and Montagne (1956) apparently influences streams flowing from the range south of Phelps Lake to turn south, parallel to the Snake River. Range-front capture of streams south of Leigh Lake to the vicinity of Taggart Lake provides evidence for topographic depression along the Teton fault in this area. This area of subsidence was revealed by a detailed topographic profile, constructed from a 1st-order level line across the valley of Jackson Hole (see **Figure 19** and discussion in the next section), which reveals up to 26 m of subsidence (Byrd and others, 1988). We suspect this topographic depression may also reflect, in part, tectonic deformation (hanging-wall subsidence) associated with prehistoric scarp-forming earthquakes on the fault. Other interpretations include an apparent westward tilt of the valley resulting from a westward flow along preexisting stream drainages emanating from the terminal moraines near Jackson Lake or aggradation of sediments deposited by the Snake and Gros Ventre Rivers. However, we agree with Love and Montagne (1956) that the juxtaposition of the westward-tilted valley block against the Teton fault is in part associated with large prehistoric earthquakes on the Teton fault.

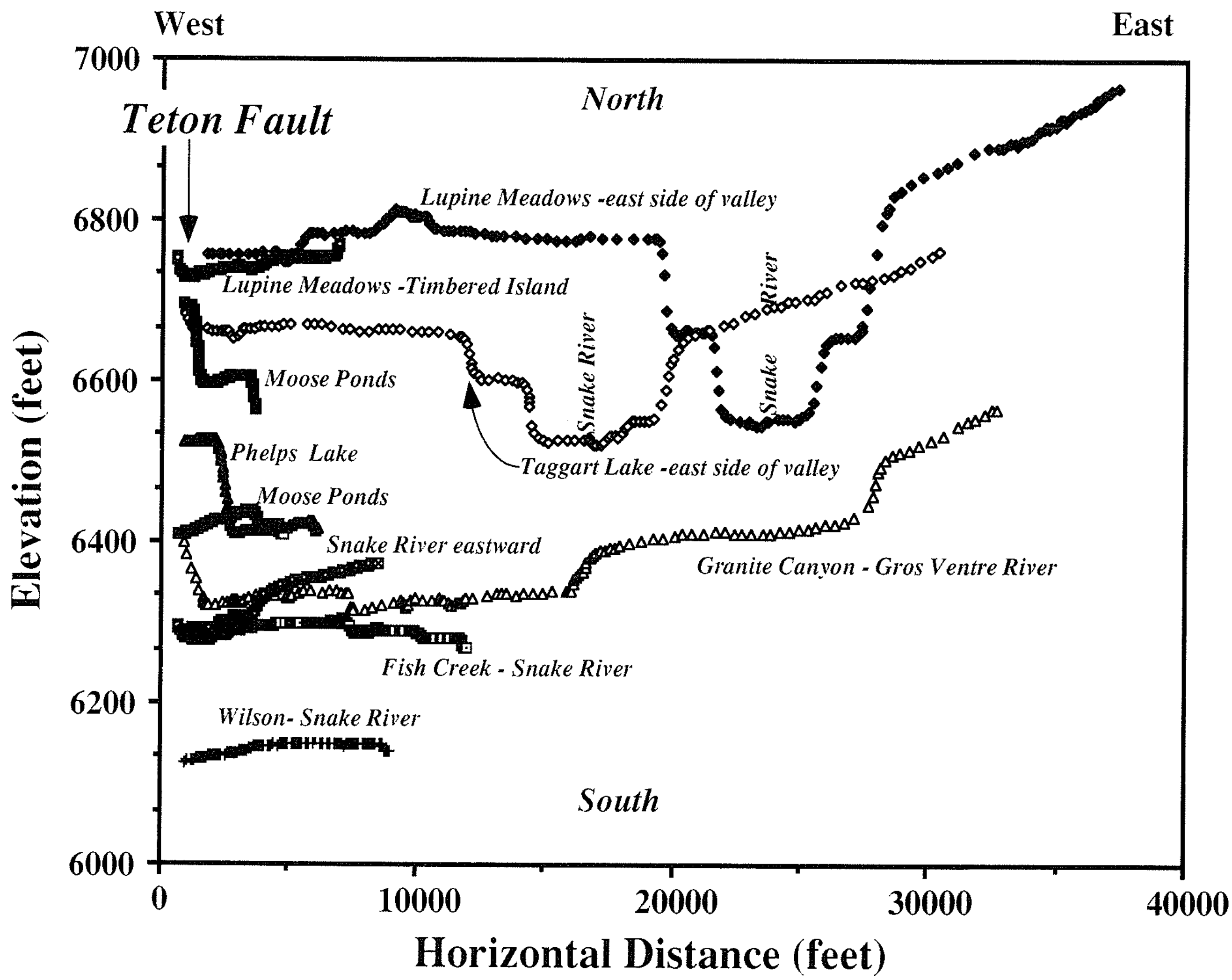


Figure 19. Topographic profiles across the floor of Jackson Hole, east of the Teton fault. Elevation data were digitized from altimeter profiles acquired by Love and Montagne (1956). Individual symbols indicate digitization points, not spacing of original altimeter readings. Heights are in feet above sea level. See Sheet 1 (Smith, Byrd, and Susong, map pocket) for geographic locations.

Contemporary deformation of the Teton fault

In a cooperative project between Professor Arthur G. Sylvester of the University of California, Santa Barbara, and the University of Utah, an east-west line of permanent benchmarks across the Teton fault was established in 1988 (Byrd and others, 1988). These marks were precisely surveyed in 1988, 1989 (Sylvester and others, 1991), and 1991. The level line was established to assess possible contemporary deformation and to provide a long-term reference frame for neotectonic studies of the Teton fault (**Figure 20** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). Only the 1988-1989 leveling data are discussed here as the analyses of the 1991 data are in progress.

The Teton leveling profile is 22.1 km long and consists of 50 permanent benchmarks at approximately 500 m intervals (**Figure 20** and **Sheet 1**, Smith, Byrd, and Susong, map pocket). The west end of the level line begins well within the footwall block of the Teton fault, near the center of the Teton Range in Cascade Canyon (**Sheet 1**, Smith, Byrd, and

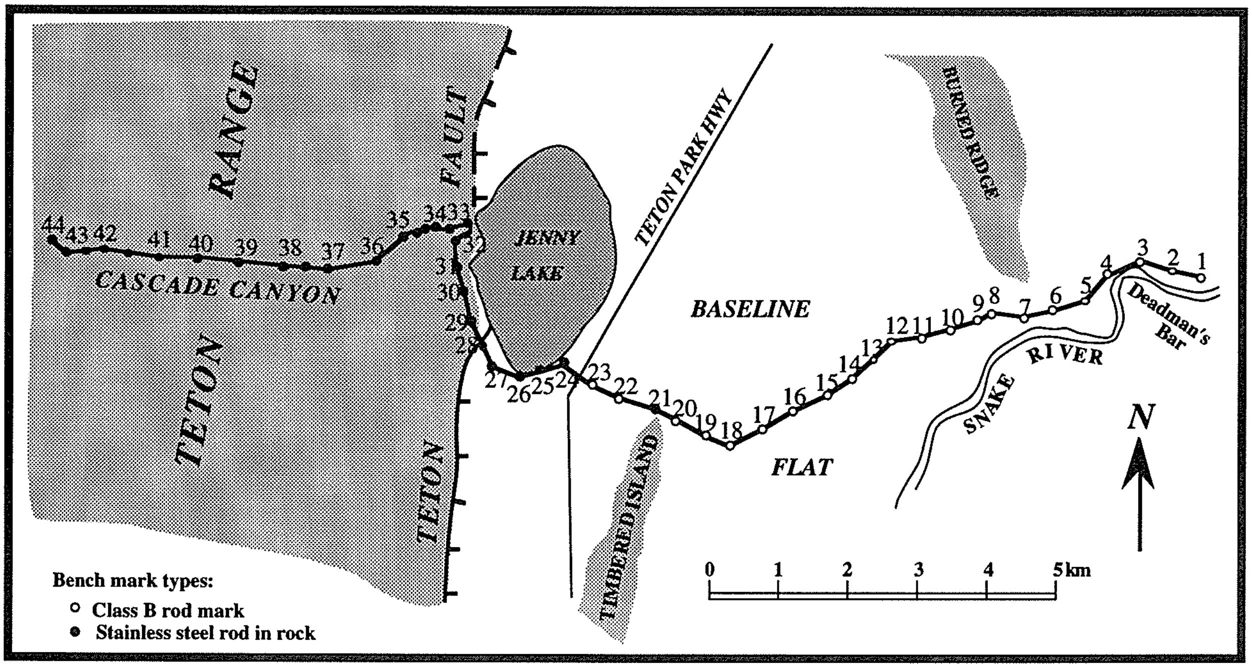


Figure 20. Map of Teton fault 1st-order level line from Cascade Canyon to Deadman's Bar (after Sylvester and others, 1991; Byrd and others, 1988). Benchmarks GT-1, 12, 24, 35 and 37 were observed using GPS (Global Positioning Satellite) receivers and will be reoccupied for future measurements of deformation.

Susong, map pocket). It extends eastward and crosses the Teton fault west of Jenny Lake and continues around the north end of Timbered Island to well within the hanging wall at Deadman's Bar on the Snake River (**Figure 21**). Details of the benchmark standards and surveying procedures are given in Sylvester and others (1990, 1991) and Byrd and others (1988). The combined observed closure of all the segments from the 1988 survey was 12.4 mm, and 12.2 mm for the 1989 survey (Sylvester and others, 1991). If the closure error is spread equally among the benchmarks for both surveys, then the probable error associated with a single benchmark is ± 0.28 mm in 1988, and ± 0.25 mm in 1989, and are equivalent to "tectonic 1st-order" surveying standards.

Results from the initial reobservation of the level line in 1989 (Sylvester and others, 1991) showed that in the one-year period, 1988 to 1989, the hanging-wall valley block rose from 4 to 8 mm relative to the westernmost benchmark within the Teton Range (**Figure 21**). The greatest height change occurred across a ~1,500 m wide zone that straddles the surface trace of the Teton fault west of Jenny Lake. These measurements indicate an unexpected reverse sense of relative motion, with the hanging wall moving up. A normal fault with the geometry of the Teton fault is expected to respond to inter-seismic tectonic loading by relative hanging-wall subsidence as in the case of co-seismic deformation observed on normal faults during large earthquakes (see **Figure 17**). Nonetheless, it is noteworthy that regardless of the sense of deformation, the displacement rate of 8 mm/yr is from 4 to 18 times greater than those determined from the geologic and paleoseismic data (**Figure 16**).

Some plausible interpretations for this unusual aseismic behavior of the Teton fault include: (1) seismic energy release on unknown faults to the east or west, such as may be associated with the background seismicity of the Gros Ventre Range, may have locked the Teton fault in horizontal compression; (2) inter-event seismic energy may be accumulating [see Sylvester and others (1991) for a complete discussion]; and (3) measurements may reflect nontectonic behavior such as ground-water flow or surveying or analysis errors. Sylvester and others (1991) preferred the conclusion that the measured displacement occurred as aseismic creep, i.e., not accompanied by earthquakes. However, the rapid change in elevation across a 1 km width argues that creep took place at relatively shallow depths, probably less than 5 km.

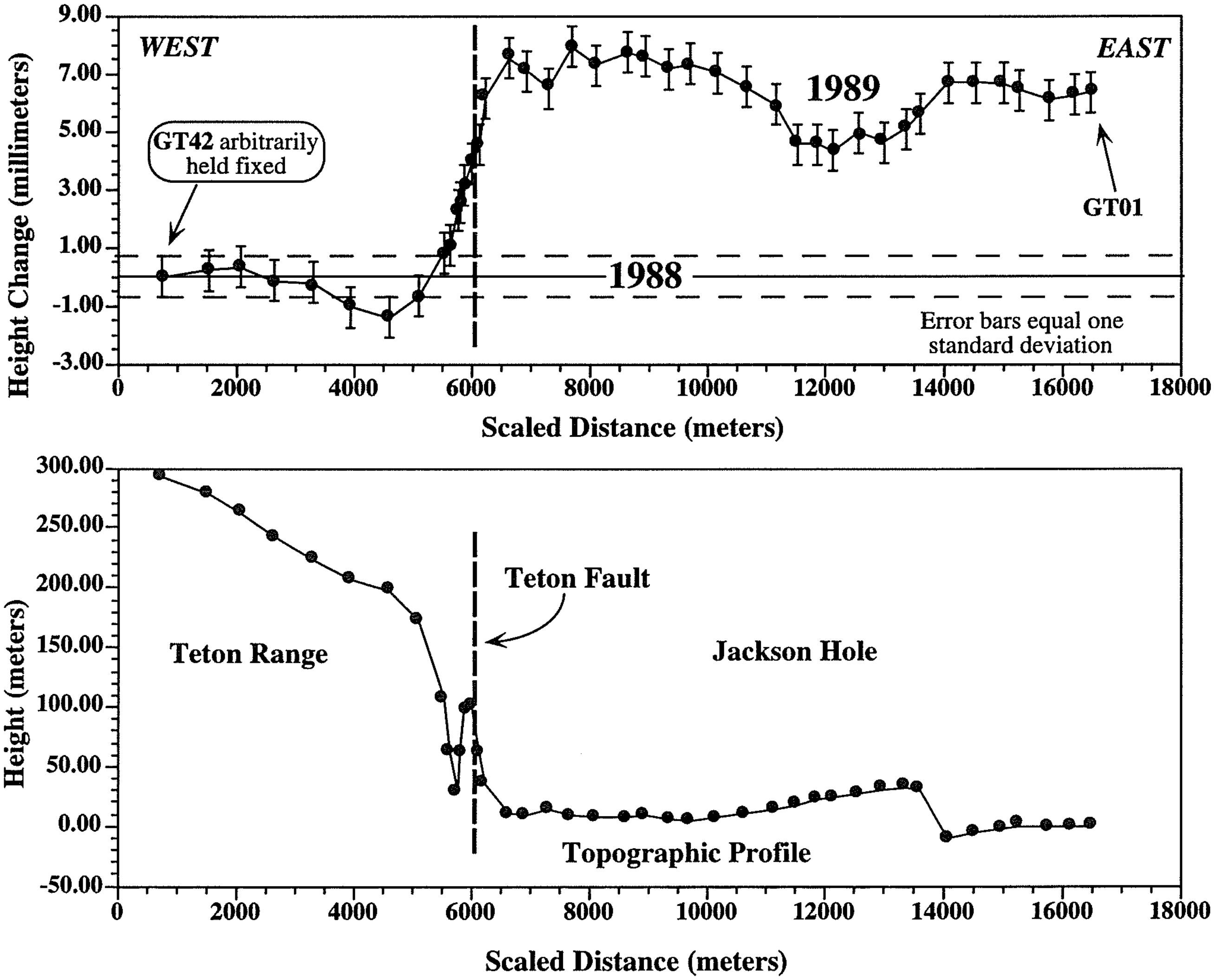


Figure 21. (a) Results from 1988 and 1989 precise leveling surveys showing height difference of benchmarks from Cascade Canyon (GT 42) to Deadmans Bar GT01 (from Sylvester and others, 1991). Elevations are in millimeters with respect to station GT42 on the western end of leveling line that was arbitrarily fixed as a zero-deformation base station. (b) Corresponding topographic profile along the Teton level line.

Preliminary analyses of the 1991 leveling results suggest that heights of benchmarks in the hanging-wall block indicate a reversal from a hanging-wall uplift to hanging-wall subsidence, with a maximum height difference of 4 mm between the 1989 and 1991 surveys. While the 1989-1991 period was also characterized by seismic quiescence along the Teton fault, these preliminary results suggest that the anomalous uplift of the hanging wall may have changed to a more characteristic deformation associated with pre-seismic loading of a normal fault (footwall uplift and hanging-wall subsidence). These observations represent the first documented occurrence of aseismic vertical creep across a normal fault in the United States.

Earthquake hazards of the Teton region

In the Teton region, contemporary seismicity and faulting are considered a natural consequence accompanying active mountain-building processes. Based on the evidence of Quaternary faulting and the historic record of large earthquakes in the ISB, future large earthquakes of M_S=6.3 to 7.5 are expected to occur every few hundred to few thousands of years (Gilbert and others, 1983; Doser and Smith, 1983; Piety and others, 1986; Smith and Arabasz, 1991). While the repeat times of large earthquakes in the ISB are large compared to the expected lifetimes of man-made structures and of man himself, the occurrence of a large earthquake in the Teton region will have a major impact on roads, structures, and human safety. Based on the results of our research and observations from historic normal-faulting earthquakes in the western U.S., we describe here possible scenarios for the Teton region in the event of a large, scarp-forming earthquake.

We emphasize that the minimum-magnitude threshold for scarp-forming earthquakes in the Basin and Range province (Arabasz and others, 1992) is $M_S = 6.3 \pm 0.3$. Furthermore, although moderate magnitude earthquakes of $5.5 < M_S < 6.3$, which occur without surface rupture, are not as large as scarp-forming events, they generally have shorter recurrence intervals (on the order of hundreds of years). Such earthquakes also pose a hazard to the Teton region because of their more frequent occurrence. Our study did not assess the attendant hazards accompanying this class of intermediate magnitude earthquakes because of insufficient data for the Teton area.

We also note that if the Teton fault has a listric geometry, as implied by one of Lageson's (1992) models, then our application of a planar, normal-faulting model derived from the large scarp-forming earthquakes of the Basin and Range province would be inappropriate. However, Jackson (1987) and Doser and Smith (1989) found no evidence of scarp-forming, normal-faulting earthquakes with dips less than 30°, implying that a listric fault model is not appropriate for normal-faulting earthquake nucleation.

Ground deformation and fault rupture

Extrapolation of data from numerical models of large normal-faulting earthquakes (**Figure 18**), coupled along with observations of the magnitude of surface rupture and displacement accompanying historic normal-faulting earthquakes around the world (Bonilla and others, 1984; de Polo and others, 1991; Mason and Smith, 1990), provide scaling laws that we used to estimate the expected magnitudes for earthquakes on the Teton fault. Applying the hypothetical working model of Smith and others (1985) and Smith and Arabasz (1991) to the Teton fault, one could expect nucleation of large-magnitude earthquakes to occur east of the surface trace of the fault on a 45°- to 60°-dipping plane and at a depth of 15 ± 5 km. Furthermore, if unilateral rupture characterizes the nucleation of the Teton fault, such as the $M_S = 7.3$, 1983, Borah Peak, Idaho, earthquake (Richins and others, 1987) and as suggested for the $M_S = 7.5$, 1959, Hebgen Lake earthquake (Bruhn and others, 1987), then potential nucleation would occur at the ends of individual segments and would propagate upward to the surface and toward the opposite end of the segment. Note that for the Teton fault, the expected nucleation (starting) point would be at the bottom of the fault, displaced 10 to 20 km to the east of the Teton Range, probably at the end of a segment boundary.

The Quaternary expression of the Teton fault is interpreted by us to consist of two or three independent fault segments 13 km to 42 km long. Extrapolation of the individual segment lengths to the magnitudes of causative normal-faulting earthquakes (after Mason and Smith, 1990) suggests a minimum $M_S = 6.6 \pm 0.3$ associated with the northern segment and a $M_S = 6.8 \pm 0.3$ earthquake associated with the south or middle segment. If the 4.1-m displacement at Granite Creek is composed of two separate slip events of 2.8 m and 1.3 m, as suggested by Byrd and Smith (1990b) and Byrd (1991), then the corresponding magnitudes of the causative earthquake would be $M_S = 7.2 \pm 0.3$ and 6.9 ± 0.3, respectively. In either case, these are large earthquakes with the potential for significant ground deformation and damage that would rupture most, if not all, the southern and middle segments.

The expected magnitudes and displacements of earthquakes along the Teton fault (**Table 2**) assume rupture of a single segment or of multiple segments. Note that the $M_S = 7.3$, 1983, Borah Peak, Idaho, earthquake ruptured one 20-km-long segment entirely and propagated about 14 km into an adjacent segment. Thus, if the southern and middle segments of the Teton fault represent a single 42-km-long segment, then a rupture of this length would correspond to an $M_S = 7.1 \pm 0.3$ earthquake using the relationships of Mason and Smith (1990).

Table 2. Expected magnitudes (M_S) and displacements for large earthquakes on the Teton fault. Estimates from scaling laws for normal-faulting earthquakes by Bonilla and others (1984) de Polo and others (1991), and Mason and Smith (1990).

Segment name	Rupture length (km)	Magnitude (M_S)	Surface displacement (m)
South	20	6.8 ± 0.3	1.0
Middle	22	6.8 ± 0.3	1.0
North	13	6.6 ± 0.3	0.5
South/middle segments combined	42	7.1 ± 0.3	2.8
Rupture of the entire length of Quaternary faulting	55	7.2 ± 0.3	4.0

Associated with these fault displacements, the valley floor of Jackson Hole could tilt westward against the fault and subside in a manner similar to that observed in other large normal-faulting earthquakes (see **Figures 17** and **18**). This effect could lead to rechanneling of rivers and streams and possible flood inundation of low-lying areas, depending upon the location of the subsidence and local hydrologic conditions. However, we cannot state unequivocally what would happen in the Teton area in the event of a large earthquake, because we do not know the actual fault attitude and geometry, stress condition, etc. Therefore, we must rely upon models of normal-fault nucleation based upon the observations of the large, historic normal-faulting earthquakes (**Figure 17**).

Ground shaking

Strong ground motions (peak ground accelerations) of the Earth's surface accompanying a major earthquake produce most of the seismically related damage to man-made structures. Strong ground-shaking occurs not only along the fault, but at distances up to several 10s of km from the surface rupture. Strong shaking damages structures and roads, produces loss of soil strength resulting in liquefaction and failure of the ground surface, and can induce rock and snow slides. Ground shaking may also be amplified at a particular site by a number of factors such as the thickness and competency of unconsolidated rocks, ground-water conditions, focusing of seismic energy due to local geologic conditions, or poor construction/design of structures. To date, there has been little research done on determining engineering properties of soils and site-specific conditions in the Teton region, therefore, a site-specific evaluation of strong ground motion and expected damage accompanying a large earthquake in this region is not possible.

Secondary effects

Secondary effects accompanying a large earthquake on the Teton fault are expected to include rock and snow avalanches, landslides, liquefaction, rechanneling of streams and rivers, and generation of seiches within lakes. The potential impact of these effects in the Teton region depends, in various ways, on the time of year, amount of precipitation, exposure to the fault, etc. For example, high runoff during wet springs may saturate soils and thus amplify the potential for landslides and liquefaction. Similarly, a heavy snow pack in the surrounding mountains would increase the threat of seismically induced snow avalanches.

Earthquake-induced landslides

The influence of earthquakes on potential landslides is particularly important to the Teton region. Investigations by Bailey (1972) and Case and others (1991) revealed the presence of large areas susceptible to landslides in the Teton, Snake River, and Gros Ventre Ranges. The earthquake-related landslide hazard of the Teton region is emphasized by Smith and others (1976), who examined the possibility that the June 23, 1925, Lower Gros Ventre slide (location shown in **Figure 7**) may have been triggered by earthquakes.

The Lower Gros Ventre slide occurred at the western end of Gros Ventre Canyon and catastrophically released 38 x 106 m^3 of bedrock that slid down the north-facing side of the Gros Ventre Canyon and dammed the Gros Ventre River (Voight, 1974). Failure of the rock-slide dam caused the disastrous Kelly flood two years later. Smith and others (1976) compiled the personal accounts of several residents living in the Gros Ventre Canyon and in the town of Moran prior to the 1925 Lower Gros Ventre slide. Their study revealed evidence for earthquake swarms and persistent background seismicity several years before this catastrophic slide. It appears that earthquakes in the Jackson Hole area were more common for several years preceding the 1925 Gros Ventre slide than for several years following the slide

(Smith and others, 1976). In their accounts, residents noted a significant increase of small earthquakes in the spring of 1925, including an earthquake of magnitude 3 to 4 in the northern Jackson Hole-Kelly area 20 hours before the slide (personal communication, Slim Lawrence to R. B. Smith). Although the evidence is equivocal, this earthquake and the persistent earthquake swarms, in the presence of highly susceptible landslide terrain, may have induced ground creep followed by the massive slide several hours later.

As pointed out in the section on seismicity of the Teton region (see **Figure 7**), the Gros Ventre Range is a seismically active area, and earthquake-induced landslides may be more common here than in other areas in the Teton region. Of course not all landslides in the region have necessarily been seismically induced, but if even a small percentage were related to earthquakes, they pose an important long-term hazard.

Other earthquake hazards characteristic of the Teton region include large rock slides and debris flows in steep canyons that could be triggered by even moderate-magnitude earthquakes. Earlier accounts of earthquakes in the region (Fryxell, 1933) told of large rock falls and avalanches occurring after small earthquakes. It is likely that a major earthquake along the Teton fault would trigger significant snow avalanches during winter months along the steep range fronts and within the steep-sided canyons of the Teton Range.

Rock falls and landslides following a moderate to large earthquake could disrupt crucial transportation routes and power lines in and out of Jackson Hole. In addition, excess water could be expelled by natural springs, which could disrupt stream and river flows. For example, in the first few weeks following the 1983 Borah Peak earthquake, up to 0.5 km^3 of ground water (Wood, 1985) was released from areas adjacent to and along the ground rupture. Similar phenomena may accompany a large earthquake along the Teton fault.

Seismically-induced waves, or seiches, in lakes along the Teton Range (such as Jackson Lake) could result from earthquakes on the northern Teton fault. Seiches accompanying the M_S = 7.5 1959 Hebgen Lake earthquake localized flooding of the shorelines of Hebgen Lake, Montana (Myers and Hamilton, 1964). It should be noted that the presence of large islands on the east shore of Jackson Lake would likely reduce, but not preclude, seiche damage to areas on the east side of the lake. However, the juxtaposition of smaller lakes adjacent to the Teton fault (**Figure 3** and **Sheet 1**, Smith, Byrd, and Susong, map pocket) increases the likelihood of damage resulting from tilting and small-scale seiches.

Conclusions

Our study reveals that the well-preserved Quaternary scarps of the Teton fault extend for 55 km at the base of the Teton Range. Since its inception 5 to 13 Ma, the Teton fault has accumulated an estimated 6 to 9 km of stratigraphic separation, including up to 28 m of surface offset in just the past 14 ka, and several meters of Holocene displacement. Thus, we believe that the Teton fault is an active structure and has been the dominant factor contributing to the 2,150 m of topographic relief of the Teton Range in at least the last 2 Ma.

On the basis of lateral offsets of Quaternary scarps, scarp height variation, and variations in trends of faulting, two to three fault segments from 13 to 42 km long have been defined for the Teton fault. Each of these segments is considered capable of rupturing during large scarp-forming earthquakes of $M_S = 6.3 \pm 0.3$ or larger. Rupture of the entire 55 km length of the Teton fault may correspond to an earthquake as large as $M_S = 7.2 \pm 0.3$.

The 3.6-m fault scarp at the mouth of Granite Canyon contrasts in offset with larger scarps, up to 13 m in height, 120 m north of the trench location. The larger scarps are the products of several scarp-forming, prehistoric earthquakes that offset 14 to 30 ka Pinedale glacial deposits. Rates of surface offset (corresponding to conservative estimates of slip rates) projected from the trench data and the adjacent scarps, suggest average slip rates of 0.45 to 1.6 mm/yr for this segment of the fault, with recurrence intervals for scarp-forming earthquakes from 1,600 to 6,000 years.

Initial interpretations of a trench at Granite Creek on the southern segment of the Teton fault revealed 4.1 m of vertical displacement in alluvial and glacial deposits. Byrd (1991) recently suggested that the slip was composed of two separate events identified by radiocarbon dating that supports a two-event, Holocene, displacement record with a 7,175 ± 100-yr slip event associated with 2.8 m of displacement and a younger event, associated with 1.3 m of displacement. Scaling of the Holocene fault displacements from historic normal faulting earthquakes to these paleo-slip events (Mason and Smith, 1990) suggests a scenario of two corresponding scarp-forming earthquakes of $M_S = 7.0 \pm 0.3$ and 6.9 ± 0.3, respectively, with estimated rupture lengths of approximately 32 km and 25 km.

In a study of the contemporary deformation of the Teton fault, Sylvester and others (1991) found that the hanging-wall block rose 8 mm ± 0.7 mm relative to the footwall block (the Teton Range) during a period of seismic quiescence between 1988 to 1989. This finding was unexpected, because an active normal fault ought to behave with hanging-wall subsidence and footwall uplift during elastic strain accumulation. The unusual deformation measured on the Teton fault has been tentatively interpreted as aseismic creep, but we cannot rule out a non-tectonic origin. Preliminary analyses of the 1991 leveling results, however, suggest that heights of benchmarks in the hanging-wall block decreased ~ 4 mm relative to those in the footwall and may be diagnostic of strain associated with loading of a normal fault. If the deformation observed across the Teton fault indeed represents the occurrence of vertical creep, then it is the first observation of this phenomenon across an active normal fault in the United States.

A possible implication for the aseismic creep on the Teton fault is that it is currently undergoing stress buildup prior to a large earthquake. This interpretation is consistent with the concept that the seismic quiescence on the Teton fault is a seismic gap that may end with a large event. Occurrence of a large-magnitude earthquake ($M_S \geq 6.3$) on the Teton fault would most likely result in significant ground deformation and disruption of roads and structures. However, smaller magnitude ($5.5 \geq M_S \geq 6.3$) but more frequent earthquakes also pose a notable hazard to the Teton-Jackson Hole area.

Acknowledgments

A project of the scope presented here represents the contributions of many colleagues, students, research managers, and friends. It also represents our long-term interest in seismotectonics and regional geophysics of the Yellowstone-Teton-Hebgen Lake region. This paper presents the principal findings of a three-year (1987-1989) research project entitled: "Earthquake hazards of the Grand Teton National Park: emphasizing the Teton fault" that was funded by the University of Wyoming-National Park Service Research Center, grant #532724. We are grateful to Mark Boyce and Ken Diem of the University of Wyoming-National Park Service Research Center who have always been interested in our projects and have encouraged this work. Funds for the 1989 and 1991 releveling surveys across the Teton fault were provided by the U.S. Geological Survey, National Earthquake Hazards Reduction Program grants #14-08-00001-G1349 and #14-08-0001-G1970. The Geological Survey of Wyoming also supported our 1991 dating and field efforts.

We gratefully acknowledge the excellent cooperation of the Grand Teton National Park staff including the superintendent, Jack Stark, and other staff members: Marshall Gingery, Peter Hayden, Roger Haney, and Patrick Smith. The Granite Creek trenching component of the Teton fault study was approved through a finding of no significant impact for the National Park Service subject environmental assessment "Trenching Teton fault" by the Acting Regional Director, Jack Neckels, dated August 17, 1989. We thank Marshall Gingery for his endeavors in obtaining approval to conduct this aspect of our study.

Arthur G. Sylvester and students from the University of California, Santa Barbara, and the University of Utah made the leveling measurements. Ronald Bruhn of the University of Utah frequently discussed with us the regional tectonic context of the Teton fault and provided insight into the mechanics of normal faulting. Gordon Jacoby of Lamont

Doherty Geological Observatory, Columbia University, kindly provided the tree-ring dating of the Teton fault at no cost to the project. The University of Utah provided support for computing. Art Sylvester and Jim Case provided critical and very helpful reviews of the manuscript.

William Hardman, Dan Trentman, Susan Olig, Adolph Yonkee, and Colin Zelt from the University of Utah, and Chris Hitchcock, Barbara Belding, and Ken Perez of University of California, Santa Barbara, assisted with the EDM profiling and trenching studies. A team of geologists with expertise in fault trenching and geology of the Teton region also assisted us and participated in a critical review of the final trenching results including: Ron Bruhn, Dean Ostenaa, William Lund, J. David Love, Jim McCalpin, and Ken Pierce. Chris Wood of the U.S. Bureau of Reclamation kindly provided earthquake data from the Jackson Lake seismic network. We also thank Jack Shea of the Teton Science School for providing housing and logistical support during our field work in 1989, 1990, and 1991.

We are especially indebted to J. David Love for his many years of encouragement, for his ideas on the geology of the region, and for graciously sharing his unpublished data with us. In addition, we thank Dean Ostenaa and Jerry Gilbert for contributing their knowledge of the Teton fault and for their help with the trenching project. We have also benefited from the discussions with Ken Pierce regarding his ideas of the Quaternary history of the region and his suggestion of the Granite Creek trench site.

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