Seismic surveys and Quaternary history of Jackson Lake, Wyoming

Frontispiece. Aerial view of the south end of Jackson Lake, Wyoming, looking southwest toward Mt. Moran (in background). Foreground shows Elk Island, with Moran Bay in right background. Jackson Lake occupies an ancestral basin developed by west-dipping hanging-wall deformation accompanying the Quaternary evolution of the Teton fault, followed by scouring by glaciers that entered the basin from the north and east. The lake basin sediments are dominantly alluvium, lacustrine sediments, and glacial debris. Photograph courtesy of David R. Lageson, Montana State University.

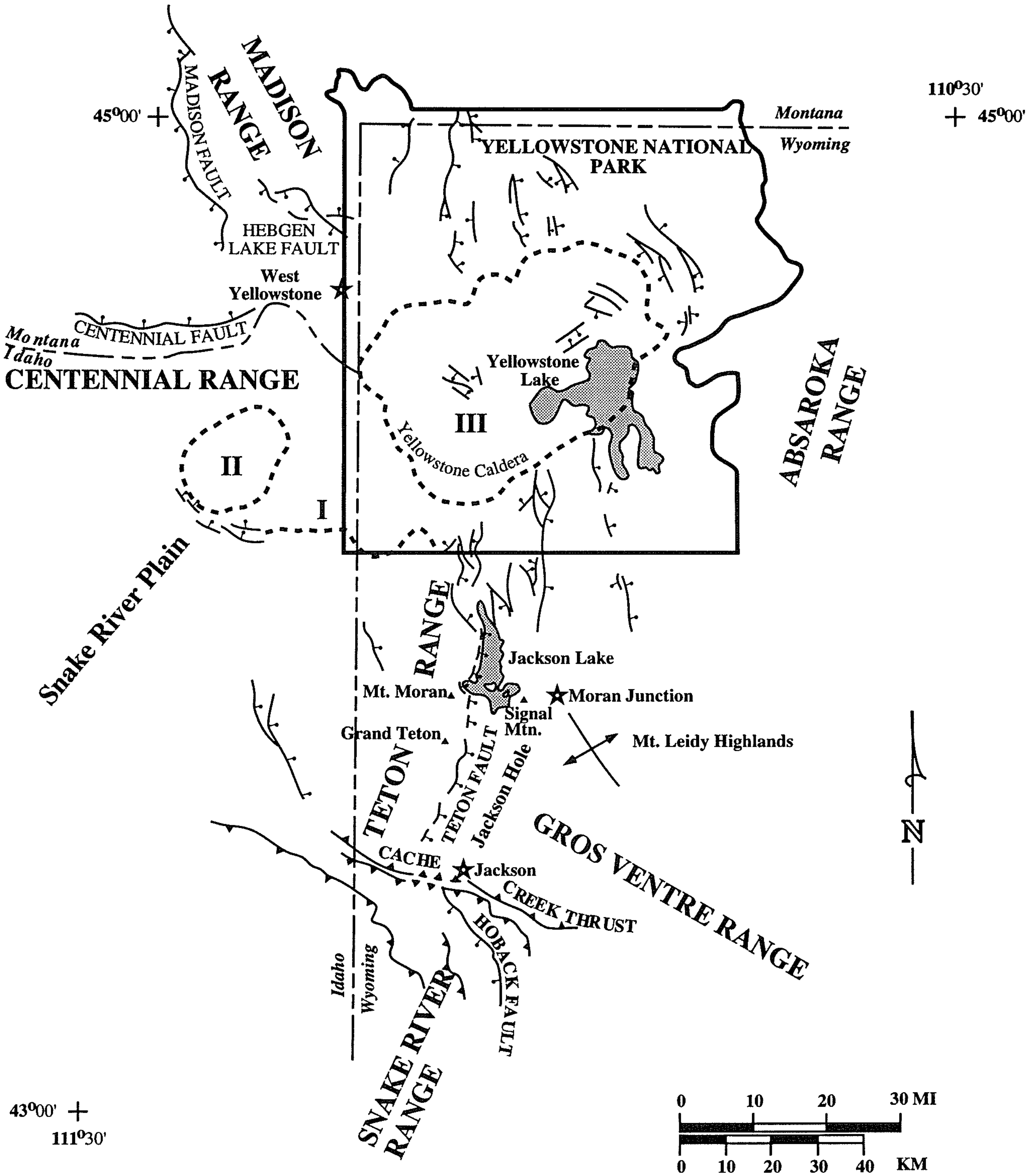

Figure 1. Regional tectonic map of the area surrounding Jackson Lake, Wyoming, showing the relationships between Jackson Lake, the Teton Range, Jackson Hole, the Teton fault, and the Yellowstone plateau and volcanic system. Outlines and ages of Yellowstone Quaternary calderas are noted: I = 2.0 Ma, II = 1.2 Ma and III = 0.6 Ma. Standard symbols for normal faults, thrust faults, and anticline.

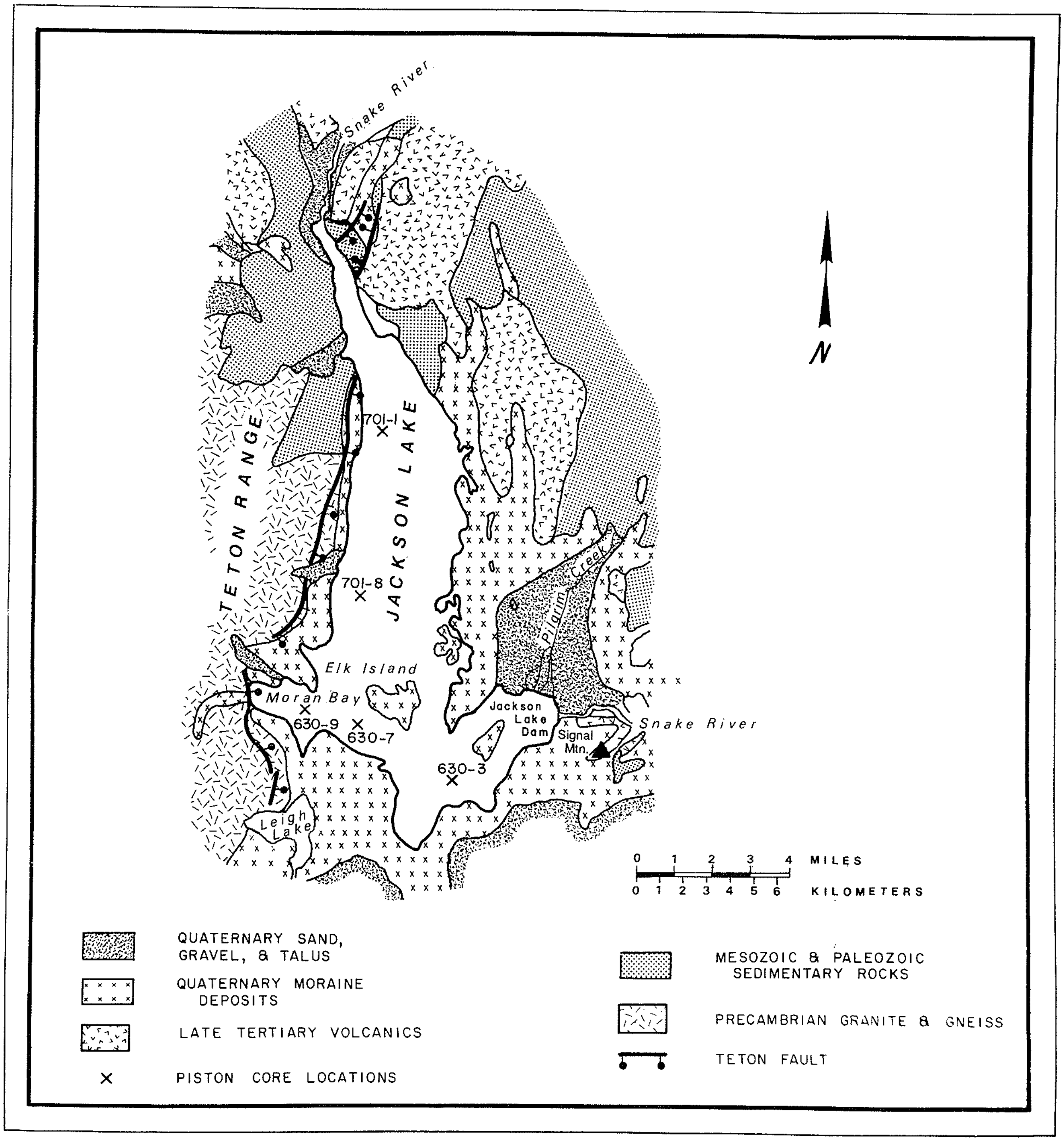

Figure 2. Generalized geology of Jackson Lake, Wyoming, area. Data compiled from Love and Reed (1971) and Reed (1973). Location of Teton fault from Smith and others (1990) and Smith, Byrd, and Susong (this volume).

Geology of the Jackson Lake area

Jackson Lake has been influenced by its proximity to the Teton Range and the range-bounding Teton fault, located immediately west of the lake (**Figures 1** and **2**). The Teton Range consists primarily of an intensely deformed and metamorphosed Precambrian gneiss and quartz monzonite core (Reed, 1973). These crystalline basement rocks are overlain by generally west- to northwest-tilted Paleozoic and Mesozoic sedimentary and late Cenozoic silicic volcanic rocks that are exposed on the west side of the Teton

Table 1. Three glacial lobes that terminated in the northern Jackson Hole region and their relative size during the three phases of the last glaciation (Pinedale). Phases are listed from youngest to oldest.

Glacial phases	(West) Snake River	Lobe Pacific Creek	(East) Buffalo Fork
Jackson Lake	XX	XX	O
Hedrick Pond	X	XXX	O
Burned Ridge	O	X	XXX

Explanation of symbols:
O = lobe not confluent with others at terminus,
X = lobe confluent but subordinate at terminus,
XX = lobe confluent and of similar size at terminus,
XXX = lobe confluent and dominates at glacial terminus.

Range (Love and Reed, 1971; Love and others, 1992). Jackson Hole and Jackson Lake occupy the hanging wall of the northern segment of the Teton fault and the regional structure suggests that Paleozoic, Mesozoic, Tertiary, and Quaternary strata extend westward beneath Jackson Lake (Behrendt and others, 1968; Tibbetts and others, 1969). Latest Tertiary ash-flow tuffs are exposed north of Jackson Lake and extend discontinuously east of Jackson Lake southward to and beyond Signal Mountain (**Figure 2**). Quaternary deposits around Jackson Lake consist mostly of glacial till and outwash with some alluvial, lacustrine, and landslide deposits. The principal units mapped by our seismic surveys were Quaternary sediments.

Information on the upper-crustal structure of northern Jackson Hole was provided by seismic refraction surveys around the western and southern margins of Jackson Lake (Behrendt and others, 1968; Tibbetts and others, 1969; Schilly and others, 1982). Interpretations of these data suggest an average P-wave velocity of 20,000 ft/s (6.1 km/s) for the crystalline basement rocks beneath Jackson Lake that were interpreted to be highly consolidated Paleozoic carbonate rocks or Precambrian granitic rocks. Paleozoic and Mesozoic strata, up to 2.5 mi (4 km) thick, are exposed on the east side of Jackson Hole (Love and Reed, 1971) and are projected to overlie Precambrian basement and also to underlie Jackson Lake.

Seismotectonics

The close proximity of Jackson Lake to the Teton fault (**Figure 2**) suggests that processes associated with large prehistoric earthquakes on this fault have influenced the structural evolution of Jackson Lake. For example, subsidence and westward tilt of the hanging-wall block of the Teton fault is consistent with westward-dipping late Tertiary volcanic units exposed in northern Jackson Hole (**Figure 2**). These include the 2 Ma Huckleberry Ridge Tuff, exposed on Signal Mountain 0.5 to 2.8 mi (1 to 5 km) east of Jackson Lake, which dips about 11° west, and an underlying 6 to 4.2 Ma tuff, also exposed on Signal Mountain, which dips approximately 22° west (Gilbert and others, 1983). The 10 to 9 Ma Teewinot Formation, exposed near Signal Mountain, dips west at 20° to 25° (Gilbert and others, 1983). The similarity of westward dips for these 10 to 4.2 Ma units implies that displacement on the Teton fault continued after 6 to 4.2 Ma (Smith and others, 1990; Pierce and Morgan, 1990; Smith, Byrd, and Susong, this volume).

Comparisons of ground deformation associated with large historic earthquakes of the Basin and Range province by Smith and Arabasz (1991) and Smith, Byrd, and Susong (this volume) suggest subsidence and asymmetric tilt of the hanging wall accompanied large, normal-faulting earthquakes. This pattern of deformation is also postulated to have accompanied large scarp-forming prehistoric earthquakes on the Teton fault, with the Jackson Lake basin occupying the subsided, hanging-wall block.

Total offset on the Teton fault is estimated to be ~18,000 to 30,000 ft (6-9 km) (Love and Reed, 1971). Quaternary scarps up to ~33 ft (~10 m) high in alluvial material and glacial moraines occur within 0.3 to 0.6 mi (0.5 to 1 km) of the west edge of Jackson Lake and reflect repeated movement along the fault from about 14 ka (Smith and others, 1990; Smith, Byrd, and Susong, this volume). Postglacial slip of up to 79 ft (24 m) has been measured southwest of Jackson Lake and at least 7,000 ft (2,100 m) of offset along the Teton fault has occurred since deposition of the Huckleberry Ridge Tuff on the northern end of the range (Gilbert and others, 1983; Smith and others, 1990; Smith, Byrd, and Susong, this volume). Estimates of Quaternary slip rates on the Teton fault by Smith, Byrd, and Susong (this volume), based upon trenching and stratigraphic offsets, range from 0.02 to 0.07 in/yr (0.4 to 1.8 mm/yr) and suggest that the fault has been an active element in the development of the Jackson Lake basin.

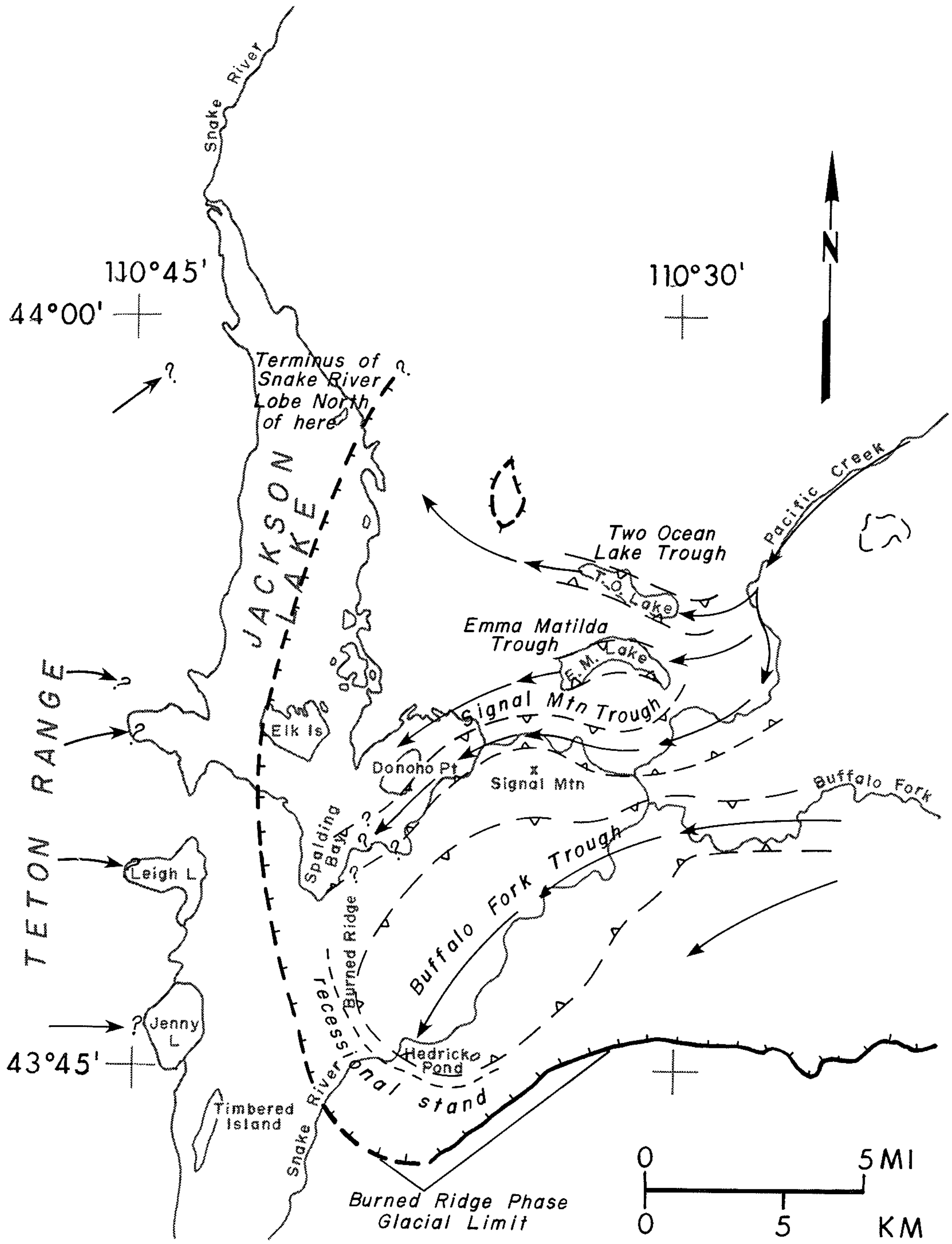

Figure 3a. Contrasting ice flow directions during the Burned Ridge phase of the last (Pinedale) glaciation. Glacial flow directions indicated by arrows. Glacial termini are shown by hachured lines except along the Teton Range where they are not known. Borders of troughs shown by long dashed line with small triangles on trough side. The Burned Ridge ice phase was associated with westward flow of the Buffalo Fork and Pacific Creek ice lobes, resulting in several glacial-scour troughs including the eastern trough of Jackson Lake

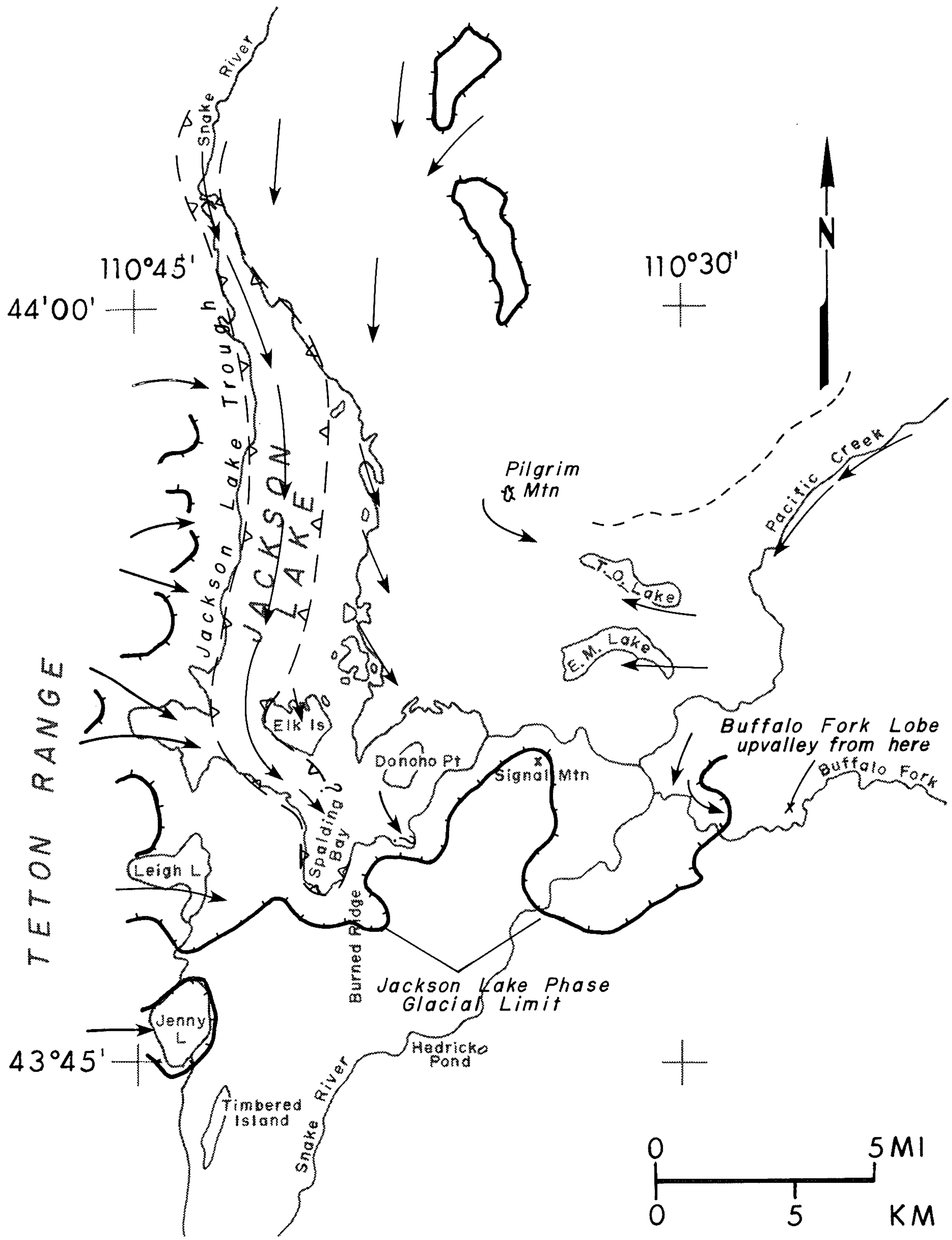

Figure 3b. Contrasting ice flow directions during the Jackson Lake phase of the last (Pinedale) glaciation. Glacial flow directions indicated by arrows. Glacial termini and ice margins are shown by hachured lines with open triangles on the ice contact side of the line. The Jackson Lake ice phase was associated with southward flow of the Snake River ice lobe that scoured the deep western trough down the main axis of Jackson Lake. Ice margins on valley walls shown by hachured line. North of Jenny Lake, the Snake River lobe was joined by valley glaciers (arrows) from the Teton Range.

Geologic mapping by Love and others (1972) and the seismic refraction studies of Behrendt and others (1968) indicated that the Teton fault extends along the western side of Jackson Lake and crosses the east side of Moran Bay. Behrendt and others (1968) and Tibbetts and others (1969) also interpreted a subsidiary north-trending fault extending through the center of the lake. However, as discussed below, we found no evidence from our reflection data for these proposed faults or any other significant faulting beneath the lake. This finding confirmed the conclusions of Smith and others (1990) and Smith, Byrd, and Susong (this volume), who reported that the main Quaternary scarp of the Teton fault is confined to on-shore areas, 0.1 to 1.2 mi (0.2 to 2 km) west of Jackson Lake.

Glaciation

Pleistocene glacial processes that scoured sedimentary troughs and deposited the extensive moraines and outwash in the Jackson Lake area are key elements necessary for understanding the seismic data and interpretations presented here. The glacial record of the Jackson Hole region was first discussed by Fryxell (1929, 1938) and later elaborated upon by Montagne (1956). Pierce (1979) described the glacial history and dynamics of the northern Yellowstone ice cap and Pierce and Good (1990) summarized their glacial geology studies conducted in Jackson Hole from 1985 to 1990.

Prior to the last glaciation (Pinedale), there were perhaps ten or more glacial intervals, during which glaciers may have reached the floor of Jackson Hole and contributed sediments to the Quaternary fill of northern Jackson Hole. The fill is estimated to be about 8,000 ft (2,460 m) thick above the 2 Ma Huckleberry Ridge Tuff just east of the Teton fault. Of these many possible pre-Pinedale glaciations, only deposits and effects of the next-to-last (Munger) glaciation are clearly identified in northern Jackson Hole. The Munger glaciation is tentatively correlated with the Bull Lake glaciation, whose age in the West Yellowstone, Montana, area is about 140 ka (Pierce and others, 1976). The Munger glaciation was much more extensive than the Pinedale glaciation; it extended about 30 miles (50 km) south of the Pinedale glacial terminus and filled Jackson Hole with more than 3,000 ft (1 km) of ice (Love and Reed, 1971; Pierce and Good, 1990).

During the Pinedale glaciation, three glacial lobes (**Figure 3a** and **3b**; **Table 1**) fed into northern Jackson Hole from the southern margin of the Yellowstone-Absaroka ice sheet (Pierce and Good, 1990). These lobes are, from east to west, Buffalo Fork, Pacific Creek, and Snake River (**Table 1**; **Figure 3a**). Three temporal phases are also distinguished, among which the relative size of these lobes changed, with the biggest lobe changing through time from sources to the east to sources north of Jackson Lake (**Table 1**). However, the ages of these phases are poorly constrained. Pinedale glaciers of the Jackson Lake phase receded from the area by 15 to 11 ka and the Jackson Lake and Hedrick Pond phases probably occurred between 40 and 15 ka. The Burned Ridge phase is at least 25 ka and may be as old as 75 ka (Pierce and Good, 1990).

During the first (Burned Ridge) phase, ice from the combined Buffalo Fork and Pacific Creek lobes flowed westward into the Jackson Lake basin nearly to the Teton Range (**Figure 3a**). At this time, the Snake River lobe did not join the other two lobes but terminated somewhere north of Jackson Lake. The ice front of this advance reached more than 6 mi (10 km) south of Jackson Lake (Fryxell, 1929; Love and Reed, 1971; Pierce and Good, 1990). This flow covered Signal Mountain and scoured deep basins north and south of Signal Mountain. The scour trough on the north side of Signal Mountain extends down the Pacific Creek valley and into the Snake River valley beneath the Jackson Lake damsite to at least the deep trough between Signal Mountain and Donoho Point (**Figure 3a**). Beneath the dike north of the concrete section of Jackson Lake dam, drilling shows that this scour basin is more than 600 ft (185 m) deep and is filled largely with unconsolidated lake sediments (Gilbert and others, 1983).

During the second (Hedrick Pond) and third (Jackson Lake) phases, ice from the Snake River (Richmond, 1973) and Pacific Creek (Richmond and Pierce, 1971) lobes joined and flowed southward into northern Jackson Hole (**Figure 3b**). At this time, the Buffalo Fork glacial lobe did not join the other two lobes but terminated several miles up Buffalo Fork. The southern margin of Jackson Lake is dammed by moraines and outwash deposited mostly during the Jackson Lake phase and built up to heights of ~100 to 300 ft (30 to 90 m) above Jackson Lake (Fryxell, 1929; Love and Reed, 1971). The deep trough beneath the long north-south axis of Jackson Lake and the drumlinoid topography on islands east of Jackson Lake were formed at this time (Pierce, 1987). This ice flowed southward to moraines about halfway up the north side of Signal Mountain. Such flow was nearly perpendicular to the westward flow during Burned Ridge time (**Figure 3a**). At this time (Jackson Lake phase), ice from the northern part of the Teton Range joined the south-flowing Snake River lobe. A glacial lobe flowing eastward from Moran Canyon through Moran Bay joined the Snake River lobe and deflected it southeastward around the southwest side of Elk Island.

Geophysical data acquisition and processing

The geophysical data for our Jackson Lake study were acquired in June and July 1974 as part of a comprehensive investigation of several lakes in the Intermountain region. A transportable 26-ft (8-m) research vessel was rigged with an air-gun seismic reflection and refraction system, a 500 cfm air compressor, a digital magnetometer, a 16-ft (5-m)-long piston corer and a high-resolution seismic-profiling device. Studies with this and similar equipment have been made of Yellowstone Lake, Wyoming (Otis and others, 1977; Nelson, 1974); Bear Lake, Utah, (Skeen, 1975); and the Great Salt Lake, Utah (Mikulich and Smith, 1974). These surveys and an earlier seismic investigation of Lake Tahoe, California-Nevada by Henyey and others (1972) demonstrated the effectiveness of marine techniques to acquire seismic information on the Quaternary geologic record in continental lacustrine environments of the western U.S.

The primary seismic reflection system used in the Jackson Lake surveys consisted of a 1-in^3 (16.4-cm^3) air gun, pressurized to 2,000 psi and fired at 4-second intervals. The data were received on a 40-element, single-channel hydrophone streamer and recorded on an FM analog recorder, providing 78 mi (125 km) of profile coverage (**Figure 4**). The 1-in^3 source had a maximum depth of penetration of about 1,100 ft (350 m) and provided a vertical resolution of ± 10 ft (3 m).

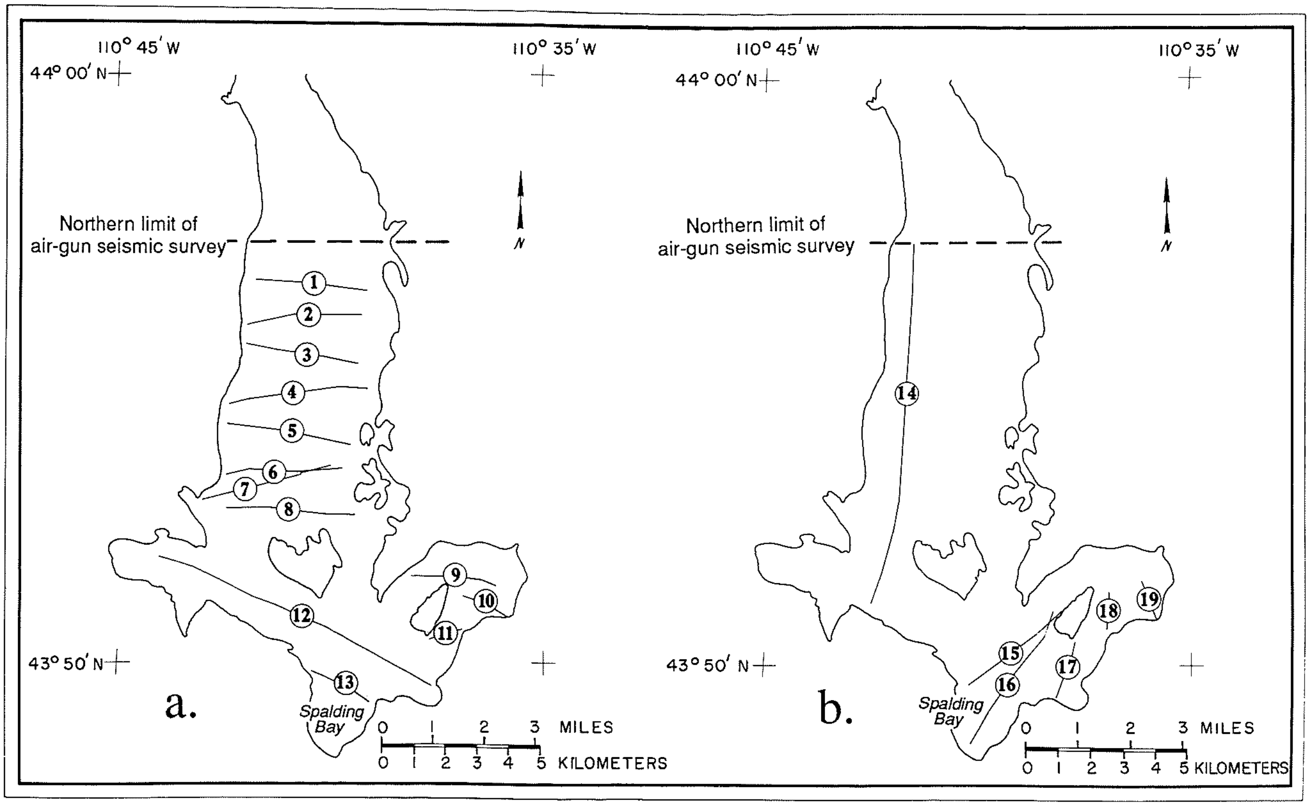

Figure 4. Index map of air-gun seismic reflection profiles of Jackson Lake. 4a numbers correspond to profiles shown on Sheet 2A and 4b numbers correspond to profiles shown on Sheet 2B.

The analog reflection data were digitized on a PDP-10 computer at the University of Utah. Homomorphic log-spectral averaging (Otis and Smith, 1976) was applied to these data to eliminate the bubble-pulse and other reverberations. Unfortunately, because none of the seismic data exist now in a digital form, we cannot reprocess them with state-of-the-art processing algorithms. The reflection data also were not migrated because of the lack of multichannel information, and also because of the lack of software for seismic processing in the late 1970s, while the data were available in a digital form.

The seismic data presented here are from both processed and unprocessed analog record sections reproduced from 9-inch, high-precision CRT displays in a continuous-tone format. Photographs were then taken of the CRT images and enlarged to obtain permanent plots of the reflection profiles. Interpretations were made on both processed and field-recorded analog record sections. We note the distortion of the reflection data ranges from 10 to 20:1 because of vertical to horizontal exaggeration.

Supplementing the seismic data, several 6.5- to 13-ft (2- to 4-m) piston cores were acquired for paleomagnetic analyses, to estimate the postglacial sedimentation rates, and to determine the composition of the sub-bottom lake sediments of Jackson Lake (Shuey and others, 1977). A radar-range microwave Mini-Ranger provided navigation for the surveys (transponder locations are shown on **Figure 5**). Locations from this system are considered accurate to about ± 3 ft (± 1 m).

Most seismic interpretations for this paper were made from the CRT-photographed seismic profiles. However, because the photographic images of the seismic record sections were not adequate for reproduction, hand-drawn picks were made to produce interpreted seismic cross sections. As an example of this process, we show two reflection profiles that

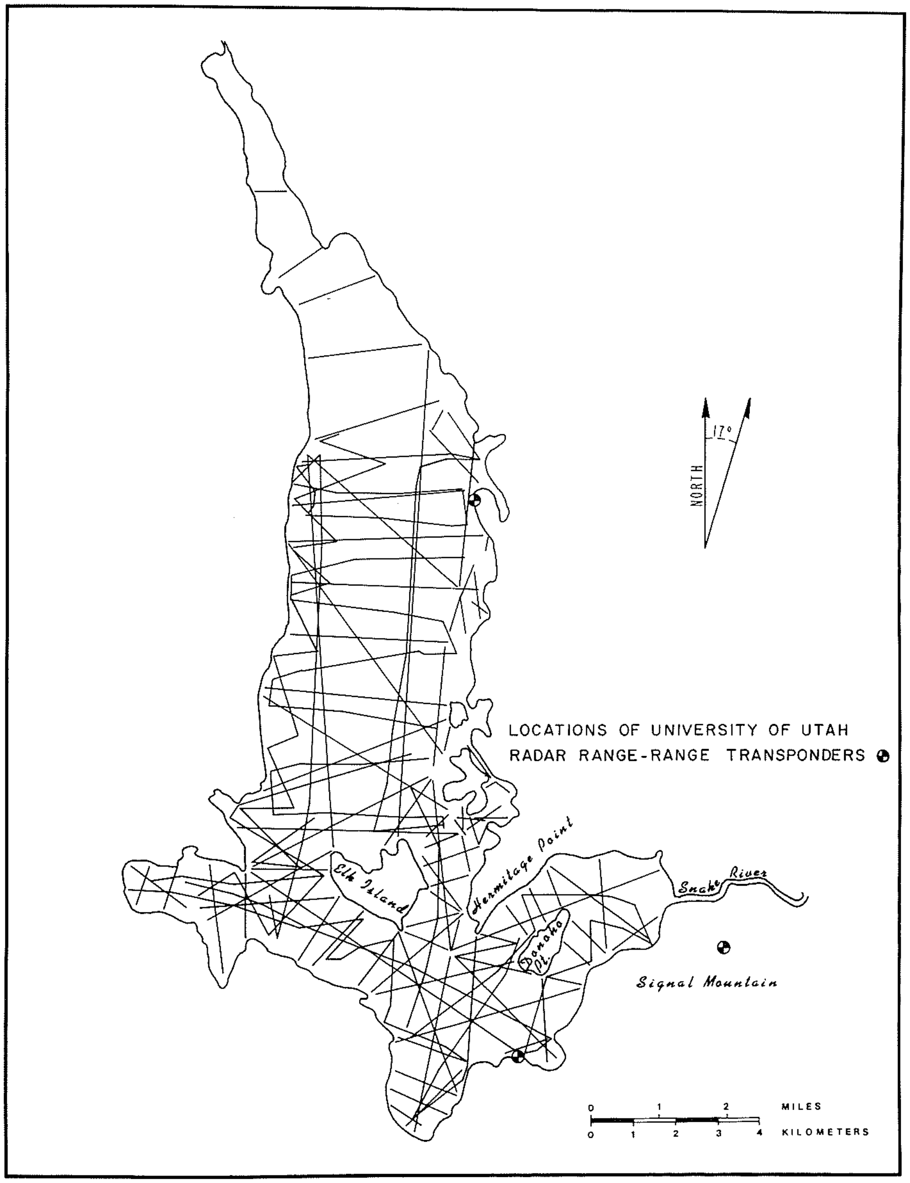

Figure 5. Locations of high-resolution seismic reflection profiles used to construct the bathymetric map of Jackson Lake. Bathymetry from 7.5 kHz high-frequency seismic reflection system with radar-range transponders for navigation. Additional data taken in areas inaccessible by our research vessel were from fathometer readings and dead-reckoning navigation by Hayden (1969).

were drawn from the accompanying photographic images in **Figures 6** and **7** (profiles 6 and 12) .

Profile 6 (**Figure 6**) extends east-west across the main Jackson Lake basin and shows our interpretation of the continuous reflectors outlining unit A, which are underlain by discontinuous and unconformable reflectors, underlain by more coherent layers C and D. Profile 12, which crosses the south end of Jackson Lake (**Figure 7**), illustrates the lack of discontinuity in reflections that are expected at the projected location of the Teton fault across the east end

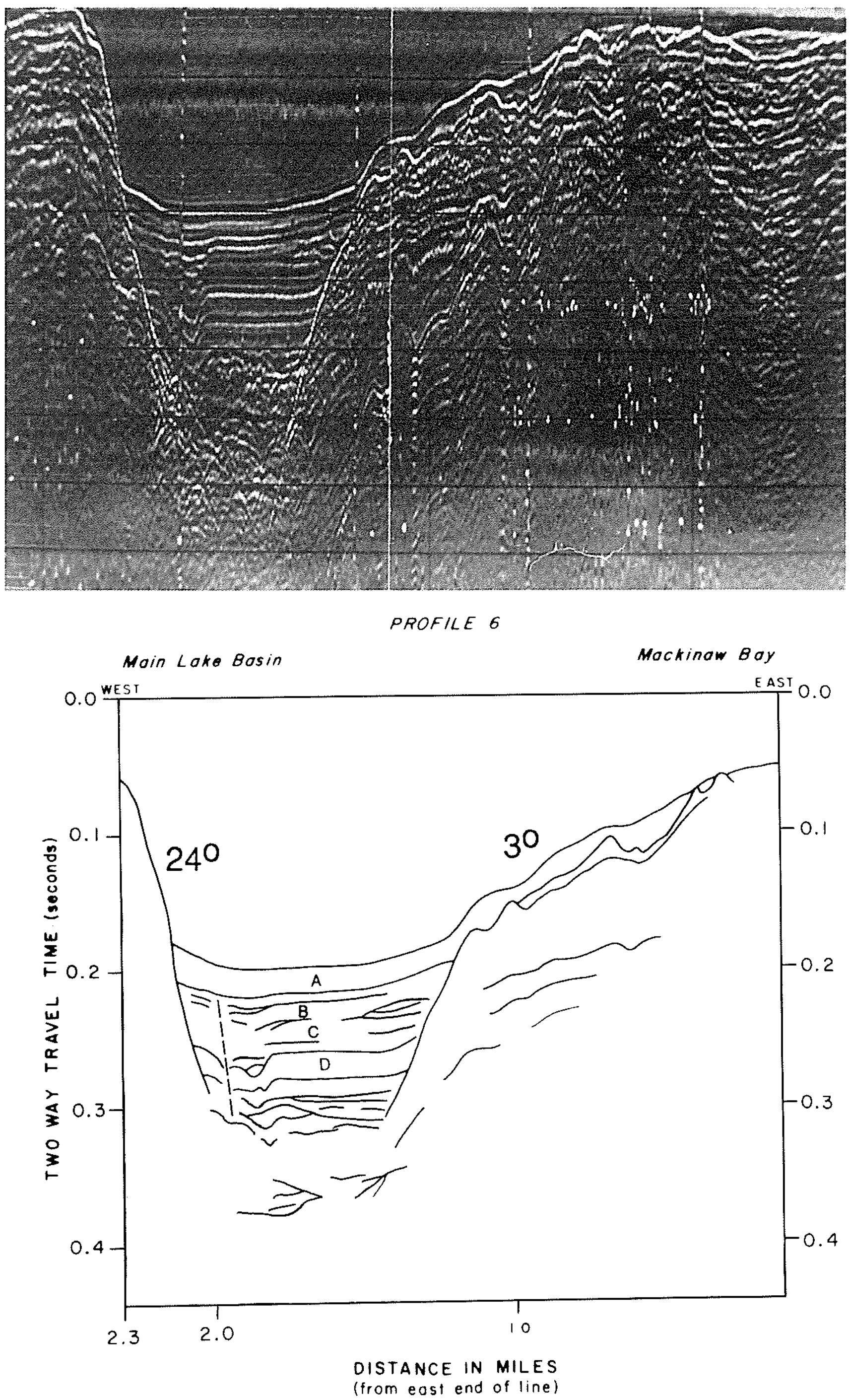

Figure 6. Seismic reflection profile no. 6 (east-west) and corresponding interpreted cross section across the main lake basin of Jackson Lake (also shown on Sheet 2A). Slopes of the water-bottom basin margins are shown in degrees.

of Moran Bay. **Figure 7** also demonstrates the excellent definition of reflector units A, B, and C in the Signal Mountain-Spalding Bay trough.

Due to the distortion caused by the exaggeration of the reflection profiles, we have noted the true dip of the water bottom on several of the figures to provide a better perspective of the lake-bottom geometry. For example, on profiles 6 and 12 (**Figures 6** and 7), the lake-bottom slopes range from 3° to 24°, representing typical values for both sides of the western lake basin. The maximum dips of the deeper geologic reflectors are correspondingly less, but they were not calculated due to the lack of migrated seismic data.

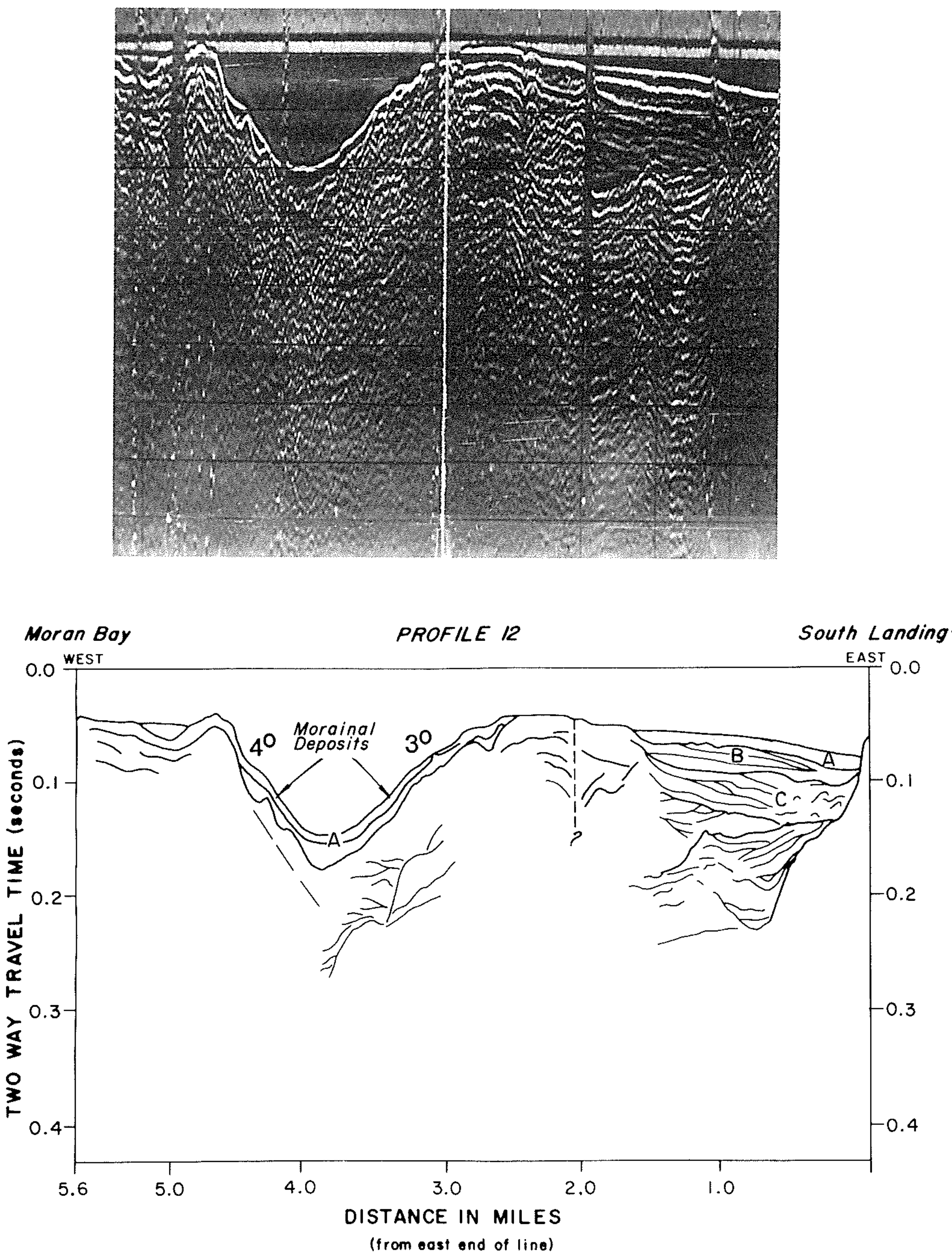

Figure 7. Seismic reflection profile no. 12 (east-west) from Moran Bay to the Signal Mountain-Spalding Bay trough with corresponding interpreted cross section (also shown on Sheet 2B). Slopes of the water-bottom basin margins are shown in degrees.

Bathymetry of Jackson Lake

An important objective of our project was to produce a detailed bathymetric map of Jackson Lake (**Sheet 1**, Smith and others, map pocket). This was accomplished by acquiring high-resolution reflection profiles of the shallow lake-bottom sediments using the 7.5 kHz-source seismic reflection system. The high-resolution data provided about 3 ft (~1 m) of vertical resolution to maximum depths of about 125 ft (~40 m) and were recorded along 207 mi (333 km) of profiles (**Figure 5**).

The depth of the water bottom was determined using the velocity of about 4,750 ft/s (1.4 km/s), determined from the refraction profiles of Oxley (1975), to convert lake bed reflections to depth. The water bottom was penetrated by five piston cores to depths of about 12-ft (4-m) and was generally composed of up to 90% fluid, grading from water into silt-sized diatom particles (Shuey and others, 1977). Thus our use of the water bottom was not at an idealized water-mud boundary, but incorporated a gradational water-to-saturated mud interface. The lake bottom is estimated to be within 1 to 3 ft (0.3 to 1 m) of the bottom of the 100% water column. Note that we were unable to acquire seismic data with our research vessel in shallow water, such as the north end of Jackson Lake on the Snake River delta and around several of the islands. In these areas we supplemented our data with fathometer depth-sounding data acquired by Hayden (1969).

From the Jackson Lake bathymetry map (**Sheet 1**, Smith and others, map pocket), two topographic troughs are apparent. The deeper western basin extends north-south and attains a maximum depth of 437 ft (133 m). A smaller eastern trough trends southwest around the north side of Signal Mountain and reaches a maximum depth of 142 ft (43 m). These troughs are separated by a shallow ridge that extends southwest from Hermitage Point. The main lake trough is bounded by generally linear margins, the western side of which has been thought to be a fault scarp. However, as noted above, the dips of these basin margins do not exceed 28° and most are less than 20°. Because the trough is two-sided (symmetrical) and much too high to represent a postglacial fault scarp, we interpret both sides of the trough to have resulted from north-to-south glacial scouring of unconsolidated Quaternary sediments deposited in a basin formed immediately east of the Teton fault.

Sediment record of Jackson Lake

The air-gun seismic reflection profiles were the primary source of data for our interpretations of the structure and sedimentation of Jackson Lake. These data consisted of 78 mi (125 km) of air-gun reflection profiles, supplemented by 207 mi (333 km) of high-resolution (7.5 kHz) reflection profiles (**Figures 4** and **5**). Nineteen of the air-gun profiles have been reproduced on **Sheet 2A** (east-west profiles) and **2B** (north-south profiles) (Smith and others, map pocket). [Also see **Figures 6** and **7** for enlarged figures of reflection profiles 6 and 12]. Examination of **Sheet 2A** and **2B** reveals that the general subsurface structure of Jackson Lake corresponds to two sedimentary basins located beneath the two bathymetric troughs, described below as the western and eastern basins.

Western basin

The shallowest distinguishable reflector marks the bottom of a unit identified as A. Unit A generally lacks strong reflectors, is widespread beneath the lake bottom, and is interpreted to represent postglacial, mostly Holocene, lake sediments. In the center of the main lake basin, unit A has a generally uniform thickness of about 55 ft (17 m) (**Figure 8**). According to analyses of 3- to 12-ft (1- to 4-m) piston cores from Jackson Lake (Shuey and others, 1977), the uppermost part of this layer consists of up to 90% water with up to 50% silt-sized diatom frustules and several percent of sand-sized detritus composed of quartz, feldspar, mica and other minerals, and up to 10% clay.

Unit A is thickest on the west side of the main lake (the west side of the bathymetric basin), reaching a maximum thickness of 70 ft (23 m) (**Figure 8**). There is little evidence (see profile 6) for westward tilt of unit A. The thickening of this layer west of the axis of the main bathymetric basin may result from turbid Snake River inflow observed to extend southward along the west side of the lake. In the eastern trough, unit A thins to about 50 ft (15 m) (**Figure 8**).

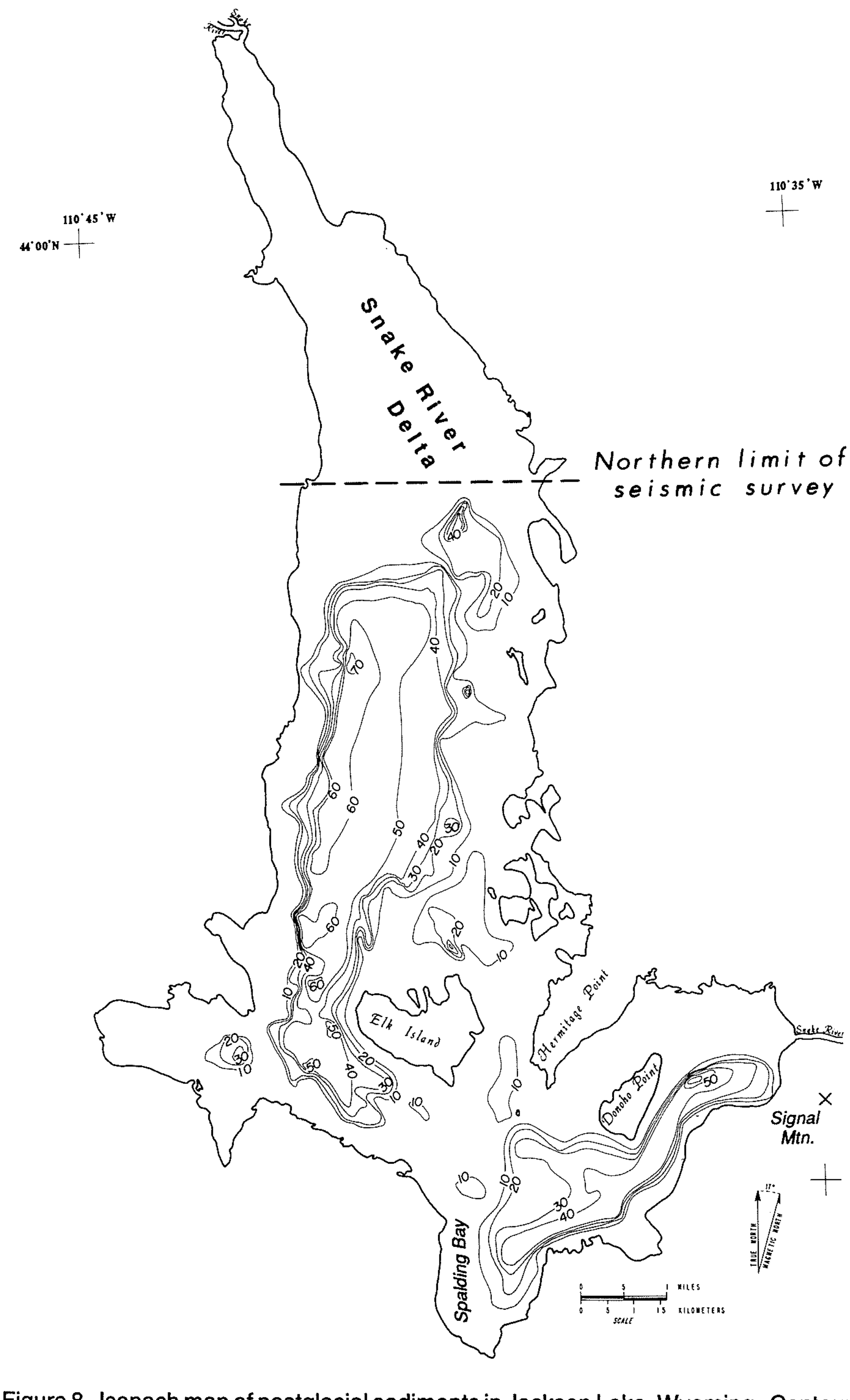

Figure 8. Isopach map of postglacial sediments in Jackson Lake, Wyoming. Contour interval = 10 ft (3.3 m). Velocity model: sediment velocity = 5,280 ft/s (1.6 km/s). This postglacial layer is interpreted to be between the lake bottom and the bottom of layer A. Thicknesses of less than 10 ft were not considered resolvable.

The seismic reflection data of Jackson Lake were carefully examined for evidence of faulting or other notable structural deformation in the postglacial sediments, primarily in layer A. However, we did not recognize any significant displacements in this layer, including across the east side of Moran Bay, where the Teton fault has been postulated by other workers (see Behrendt and others, 1968; and Love and others, 1972).

As seen in profiles 1 through 8, unit A averages 55 ft (16 m) thick, and piston cores of the upper 6.5 to 13.1 ft (2 to 4 m) from this unit show that it is composed dominantly of diatoms (Shuey and others, 1977). Dissolved silica, necessary to form the diatomaceous sediment, probably came from thermal springs in the Yellowstone volcanic plateau drained by the Snake River. This composition suggests that unit A was accumulated by a rain of diatoms growing in waters of a relatively clean lake. The environment of deposition has probably remained essentially unchanged since the drainage basin was deglaciated in the latest Pleistocene time.

For the main lake basin, units B and C (for example on profile 3, **Sheet 2A**) are noted as packets of discontinuous reflectors and are bounded by unconformities. These units are also evident on profile 6 (**Figure 6**). At the north end of the main lake basin, the seismic data reveal a more erratic nature of reflections in units B and C (between units A and D) that are marked by short discontinuous reflections and diffractions (profiles 3, 4, and 5, **Sheet 2A**). Units B and C apparently represent more disturbed sediments characterized by discontinuous reflections and unconformities. As shown in profile 14 (**Sheet 2B**), the slopes of units B and C decrease from north to south. This slope variation is consistent with their derivation from sources at the north end of the lake, perhaps by slumping from the Snake River delta and southward transport of this watery sediment mass by gravity into and along the deep western trough.

While there are deeper discontinuous reflections, unit D is the deepest coherent reflection package that was visible in our data. On reflection profiles 3, 4, 5, 6, and 7 (**Sheet 2A**), layer D can be recognized as a set of weak discontinuous reflections at 0.25 to 0.30 s (two-way travel time). The homogeneous nature of this unit suggests that it was deposited during a period of continuous deposition, although the possibility of multiple reflection paths cannot be ruled out. Beneath layer D, a zone of discontinuous reflectors makes up the deepest sediments seen in the reflection data of Jackson Lake at depths of 660 to 980 ft (200 to 300 m). However, these reflectors lack the lateral continuity to identify them as separated sediment packages (**Sheet 2**), although their internal character is similar to that of units B and C.

In the center of the main-lake basin, profiles 3 through 7 (**Sheet 2A**) show that the sediment packages A, C, and D have dips generally less than 5°. At the north end of Jackson Lake, a gentle eastward dip on these units can be seen on profile 1 (**Sheet 2A**), opposite to that expected for a westward tectonic backtilt. On profile 8 (**Sheet 2A**), at the south end of the main basin, the reflectors beneath the coherent sediment layers dip westward on the east side of the basin. We interpret that the western basin (**Figure 9**) contains at least 375 ft (115 m) of sediments (see profile 14, **Sheet 2B**; and profiles 1 through 8, **Sheet 2A**). South of Elk Island (profile 12, **Sheet 2A**), either the base of the sediment-filled trough rises to the base of unit A or the set of recessional glacial moraines south of Elk Island have restricted adequate seismic imaging of underlying reflectors.

The sediment supply to Jackson Lake during late glacial time was probably greatest into the Snake River delta at the north end of Jackson Lake. Also, layer A is thinnest or absent near the Snake River delta, where deposition of terrigenous clastics continued into the late Holocene. As will be discussed later, the deepest part of the inferred scour basin is north of the currently deepest part of the lake, also suggesting a northern source of sediment (profiles 1 through 8, **Sheet 2A**). However, unit A is also commonly absent in the shallow parts of the lake basin, possibly scoured away by modern lake currents as fast as it accumulates.

Secular changes of remnant magnetization from four piston cores extracted from Jackson Lake (locations on **Figure 2**) were analyzed by Shuey and others (1977) to estimate paleoinclination for the past ~ 1,800 years. They concluded that the sharp swings in inclination correlate among the four cores (as shown by the dashed lines in **Figure 10**). The time scale was determined by comparison with the archeomagnetic data of the western U.S. described by Shuey and others (1977). From these paleomagnetic data, the predicted paleomagnetic inclination curves indicate a maxima at 1175 A. D. and a minima at 800 A. D. and lead to estimates of the sedimentation rates for the youngest sediments in Jackson Lake (**Table 2**).

The sedimentation rates determined for the uppermost sub-lake bottom sediments of Jackson Lake (**Table 2**) ranged from 0.04 to 0.08 in/yr (0.11 to 0.21 cm/yr) for the period 800 to 1175 A.D. and from 0.04 to 0.06 in/yr (0.09 to 0.15 cm/yr) for the period 1175 to 1974 A.D. Averaging these rates gives a range of 0.04 to 0.07 in/yr (0.09 to 0.17 cm/yr) for about a 800 to 1,900 year interval with an average of 0.06 in/yr or 5 ft/1,000 yr (0.14 cm/yr or 1.4 m/1,000 yr).

The minimum age of unit A, calculated using the layer thickness and the average sedimentation rate, is about 10,000 years and is notably less than the 14,500-year age of the near-total deglaciation of Yellowstone Lake (Porter and others, 1983). However, the sedimentation rate used for this calculation is based on only the upper one-tenth of the thickness of unit A, and the expected compaction of this unit with depth would result in a closer match between the age of deglaciation based on sedimentation and that based on carbon-dating.

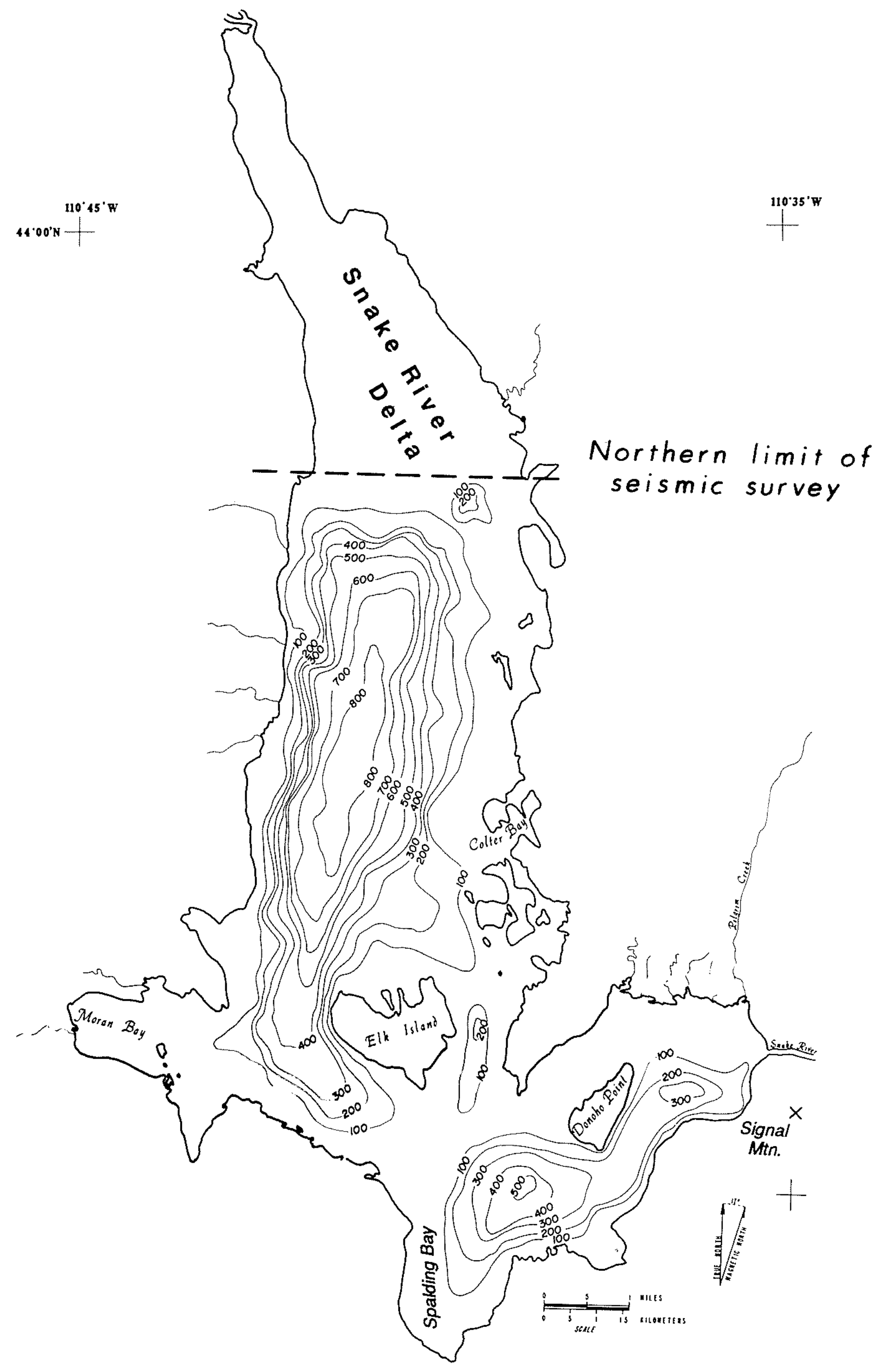

Figure 9. Depth to base of poorly consolidated Quaternary sediments in Jackson Lake, Wyoming. Contour interval=100 ft (30.5 m). Datum is the surface of Jackson Lake in 1974. Velocity model: water velocity = 4,785 ft/s (1.45 km/s), sediment velocity = 5,280 ft/s (1.6 km/s). Isopachs of sediment thicknesses can be determined by subtracting the bathymetrically determined depths on Sheet 1 (Smith and others, map pocket) from data in this figure.

Sediment units B and C are generally much thicker than layer A, and their ages are not known. However, they are considered to date from the time when sediment delivery by the Snake River was quite high. A large increase in deposition rate, perhaps fifty times greater than that characterizing the Holocene, determined here from the paleomagnetic analyses, is required for an interval of a few thousand years. This is not unreasonable because: (1) deposition rates in water bodies near glaciers are typically very high (decimeters/yr), and (2) the 40:1 ratio of the sediment source area to deposition area would result in a strong sediment-focusing effect. The western trough of Jackson Lake has an area of about 9.6 mi^2 (25 km^2), whereas the glaciers draining into the basin had an area of about 380 mi^2 (1,000 km^2). Thus the high rate of late-glacial accumulation in not unreasonable.

The deeper coherent units, B and C, are identified at their tops and bottoms by unconformities (see for example, profiles 3, 5, and 6, **Sheet 2A**). Plausible interpretations for the unconformities are: (1) partial erosion of the sedimentary fill deposited by a glacial advance, followed by deposition of more sediment; (2) periodic lowering of lake levels by at least several hundred feet with ensuing subaerial erosion, followed by raising of lake level and renewed lake deposition; and (3) slumps of water-rich unconsolidated sediment from the steep front of the Snake

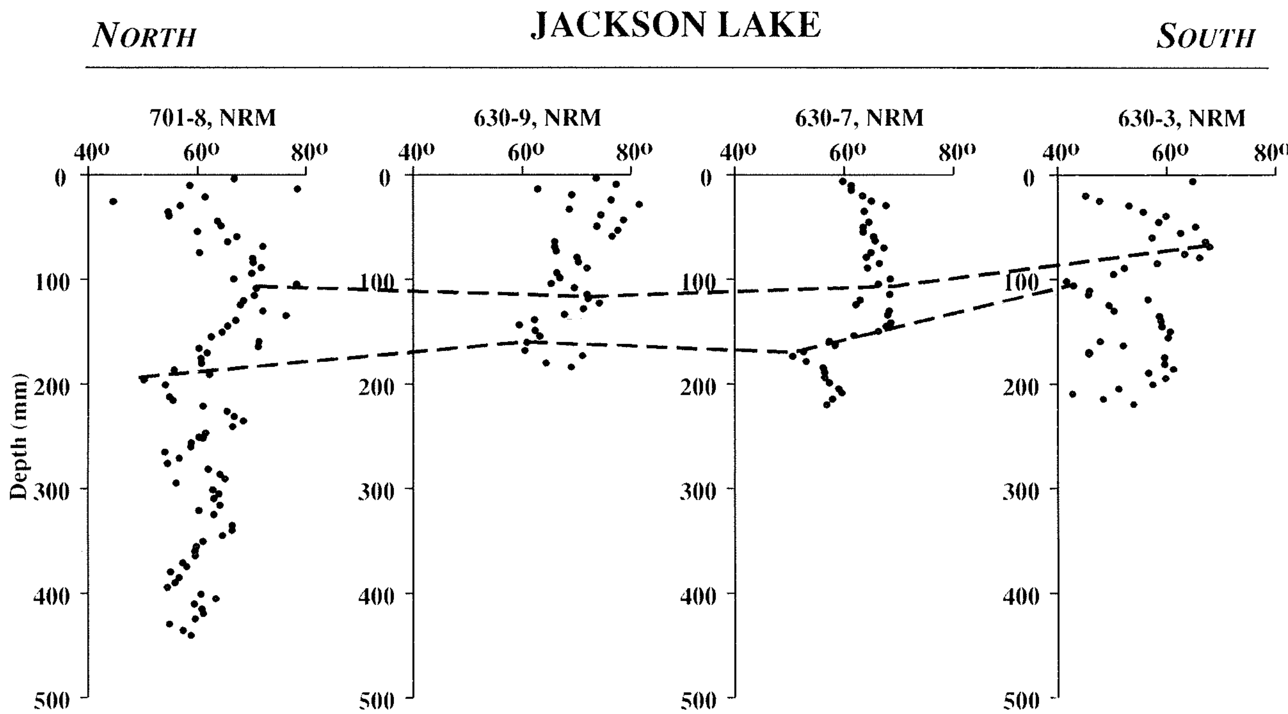

Figure 10. Correlation of paleomagnetic inclinations from piston cores (dashed lines), Jackson Lake, Wyoming (modified from Shuey and others, 1977). See Figure 2 for piston core locations. The data are NRM (natural remnant magnetization) and were demagnetized in fields of 50, 100, or 150 oersteds.

River delta and gravity transport of this sediment mass to the floor of the deep trough, producing contorted sediment packets with relatively flat tops.

The first explanation is considered unlikely because any significant overriding by glacial ice would probably scour out all the soft sediment and because glacial overriding is not likely to leave a similar section everywhere along the trough. A more plausible variation of the first explanation might include glacial standstills or minor readvances of about 0.6 mi (1 km) during overall retreat of ice northward.

The second explanation is considered unlikely because the lowest level of the lake is currently controlled by a bedrock threshold at the Jackson Lake dam site at an elevation of 6,700 ft (2,045 m). The discontinuities in the reflection profiles are all greater than 100 ft (300 m) deeper than this threshold, and displacements more than 100 ft (300 m) on the Teton fault would thus be required for base-level changes of this magnitude.

The third explanation seems plausible. Slumping of sediment from the Snake River delta at the north end of the lake and the development of southward-flowing mass movements down the trough may be responsible for units B and C, separated by planar unconformities. Slumped and rotated beds may also produce inclined layers truncated by subhorizontal unconformities. Such slumps are likely to have occurred during large scarp-forming earthquakes on the Teton fault. Large earthquakes on the Teton fault are estimated to have occurred at intervals averaging 1,600 to 6,000 years (Smith and others, 1990; Smith, Byrd, and Susong, this volume), and there have probably been several large, scarp-forming earthquakes since deglaciation about 14 ka. If such slumps oc-

Table 2. Sedimentation rates [in/yr (cm/yr)] calculated from paleomagnetic data of piston cores from Jackson Lake, Wyoming (after Shuey and others, 1977). Piston core locations shown in Figure 2.

Core no.	800-1175 A.D.	1175-1974 A.D.	Averaged by core
701-8	0.08 (0.21)	0.06 (0.15)	0.07 (0.17)
630-9	0.05 (0.13)	0.06 (0.15)	0.06 (0.15)
630-7	0.07 (0.17)	0.06 (0.14)	0.06 (0.15)
630-3	0.04 (0.11)	0.04 (0.10)	0.04 (0.10)
Averaged by age	0.06±0.02	0.05±0.01	0.06 ±0.01

curred, they most likely formed in late-glacial time and not in Holocene time, because unit A reaches its full thickness in the main trough, suggesting units B and C are pre-Holocene in age.

Eastern basin

Similar sedimentary layers, identified in the western, main-lake, basin are also present beneath the eastern bathymetric trough that consists of two sub-basins: Spalding Bay and Signal Mountain. They are described separately because the Spalding Bay trough has a more complex genesis, having been occupied and scoured(?) first by the southwest-flowing Pacific Creek lobe in Burned Ridge time and then by the south-flowing Snake River lobe in Jackson Lake time. The seismic data for this area (see profile 12, **Sheet 2A**; profiles 18 and 19, **Sheet 2B**) correspond to a total sediment thickness of about 600 ft (180 m). Other profiles—10 and 11 (**Sheet 2A**) and 17 (**Sheet 2B**)—reveal sedimentary fill of only about half this thickness. However, the bases of the scour troughs may not be apparent on these profiles and thus may be much deeper.

A continuity of main reflectors between the western (main) and eastern sedimentary troughs was not visible from our seismic reflection data. This area, however, corresponds to the location where westward-flowing ice from the Pacific Creek and Buffalo Fork lobes would have coalesced with the south-flowing ice of the main lake basin southwest of Hermitage Point. This configuration may have produced a ridge of more consolidated lateral morainal sediments that could not be penetrated by our seismic reflection system.

Spalding Bay sub-basin

Beneath Spalding Bay, sedimentary units B and C generally have eastward dips of a few degrees (less than 5°) and some have basal angular unconformities (**Figure 7**; profile 12, **Sheet 2A**). Profiles 15 and 16 (**Sheet 2B**) are located in the same area as profile 12 but show essentially horizontal bedding in units B and C, indicating that the apparent dips shown in profile 12 are essentially the maximum dips. These gentle east dips suggest deposition from a source to the west and are thought to indicate subaqueous density flows of sediment emerging into a lake from the base of the Snake River lobe when it terminated south of Elk Island. Two ages relative to the glacial sequence might be postulated: (1) units B and C on profile 12 accumulated during recession of ice from the Jackson Lake position, when a glacier front was between Elk Island and Hedrick Pond area; or (2) unit C accumulated during the Hedrick Pond glacial advance and unit B accumulated during recession from the Jackson Lake phase. The second option seems less likely because the advance to the Hedrick Pond position seems likely to have eroded unit C.

Signal Mountain sub-basin

Several hundred feet of sediment fill are present beneath the trough adjacent to Signal Mountain. Dips of beds in units B and C in this area are not systematic, as in the western main lake trough. For layer B, the following apparent dips are indicated: west (profiles 10 and 11, **Sheet 2A**), north (profile 18, **Sheet 2B**), and south (profile 19, **Sheet 2B**). For unit C, apparent dips are south (profile 18), and north (profile 19). Perhaps these diverse directions represent subaqueous filling by density flows pouring around both ends of Donoho Point and into the trough from the northwest and northeast.

Structure of the Jackson Lake basin

The upper crustal, basement structure of northern Jackson Hole has been evaluated by seismic refraction profiling around the east and south ends of Jackson Lake. Two-dimensional interpretations of refraction data were made by Behrendt and others (1968) and Tibbetts and others (1969), who interpreted Mesozoic and Paleozoic consolidated sediments to be as deep as 13,120 ft (4,000 m). These layers are interpreted to underlie Jackson Lake.

Information on the Jackson Lake sub-basin units was also interpreted from seismic refraction and wide-angle reflection data acquired in our surveys. These data were initially interpreted by Oxley (1975) but have been reinterpreted by us using new ray-tracing codes. The seismic refraction data were recorded with a fixed, radio-telemetered, single-channel sonobuoy from a moving 40-in^3 (650-cm^3) air gun on the research vessel. Seven refraction profiles were recorded in the main basin and across the south end of the lake (**Figures 11** and **12**). We discuss the generalized one-dimensional velocity determinations first (**Figure 11**), then summarize the two-dimensional structure of the southern end of Jackson Lake (**Figure 12**) using wide-angle reflection data.

To determine the general Jackson Lake basin structure, P-wave arrivals from the refraction profiles (**Figure 11**) were used to determine one-dimensional P-wave velocity models for Jackson Lake (**Figure 12**). We note that the refraction profiles were not well reversed because of the low-energy source and the resultant lack of reciprocity. The one-dimensional P-wave models were then combined into a three-dimensional diagram to display a generalized velocity model for Jackson Lake (**Figure 12**), which extends to depths of about 975 to 1,100 ft (300-400 m).

Figure 12 shows that the first layer is representative of the water column. The water layer is in turn underlain by a second layer of unconsolidated sediments characterized by an averaged velocity of 6,890 ft/s (2.1 km/s). This layer generally coincides with sediment layer A interpreted from the reflection data, and it is interpreted as upper Quaternary. This layer is thickest [~ 650 ft (200 m)] at the north end of the main lake basin, suggesting filling of a glacial scour basin by the Snake River delta and slumps from that delta. The second sediment layer underlies the entire lake and appears thickest [~ 1,000 ft (300 m)] in the center of the main lake basin. Its velocity of 8,530 ft/s (2.6 km/s) reflects increasing consolidation with depth and age compared to the lower velocity overlying layers. This layer is inter-

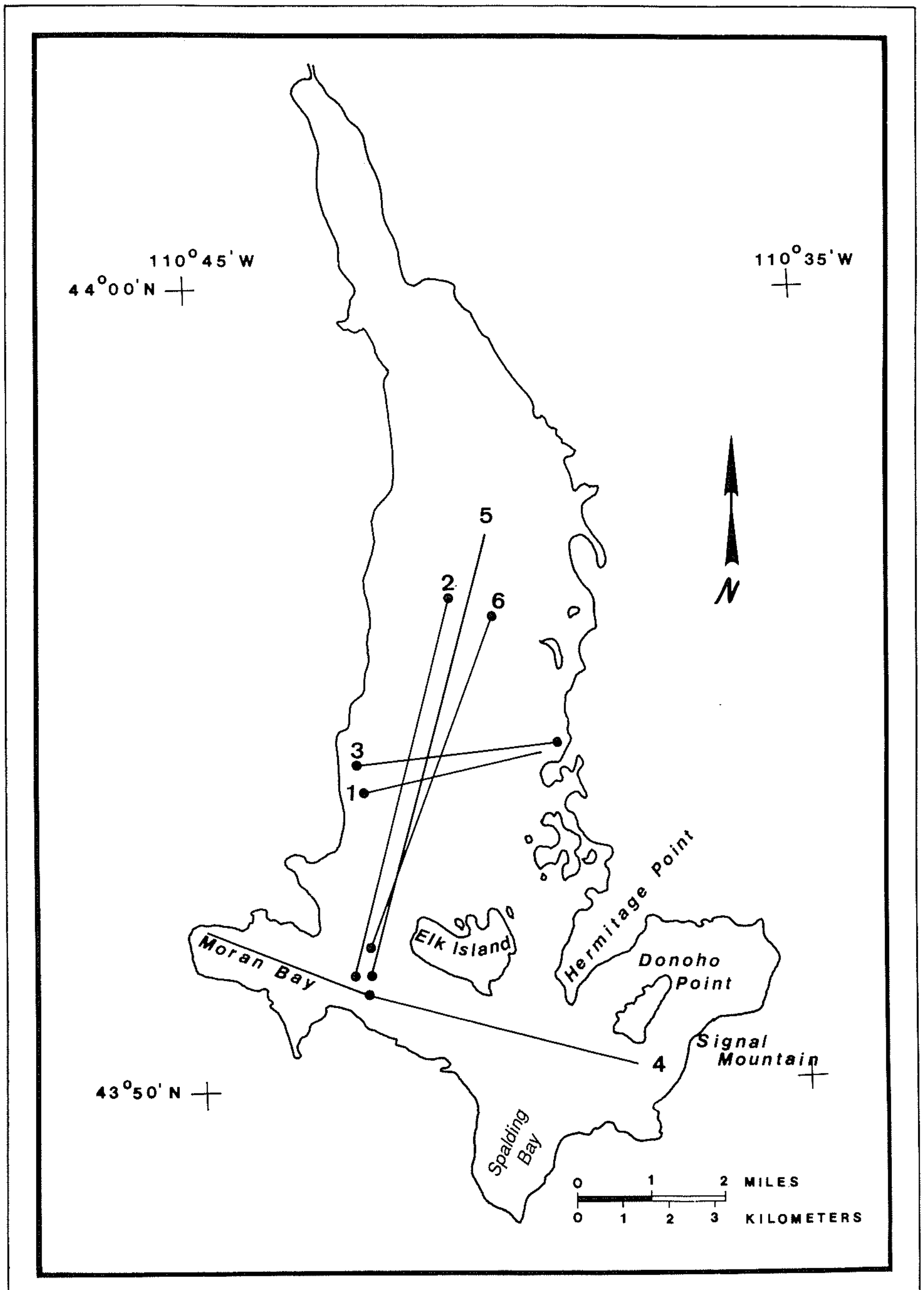

Figure 11. Locations of refraction profiles used to construct the generalized velocity structure of Jackson Lake basin. Fixed sonobuoys were located at the ends of the profiles (shown as solid dots). Note that there are two off-end seismic profiles across the southern end of Jackson Lake recorded from a single sonobuoy southwest of Elk Island.

layers. This layer is interpreted to be composed of lower Quaternary sediments, into which the late Pleistocene (Pinedale) glacial scour trough was excavated.

The third sediment layer has velocities of 11,480 ft/s (3.5 km/s) to 14,760 ft/s (4.5 km/s) and is interpreted to be composed of consolidated Tertiary and Mesozoic deposits (**Figure 12**). The deepest units discernible from the refraction data likely represent Mesozoic or Paleozoic rocks, interpreted by Behrendt and others (1968) from nearby refraction measurements south of Jackson Lake, with velocities of 8,040 ft/s (2.45 km/s) to 12,800 ft/s (3.9 km/s). Deeper Paleozoic and Precambrian rocks, identified by Behrendt and others (1968), Tibbetts and others (1969), and Schilly and others (1982), have considerably higher velocities of 20,000 ft/s (6.1 km/s) and occur at greater depths (~ 10,000 ft/ 3 km) than penetrated by our seismic profiles.

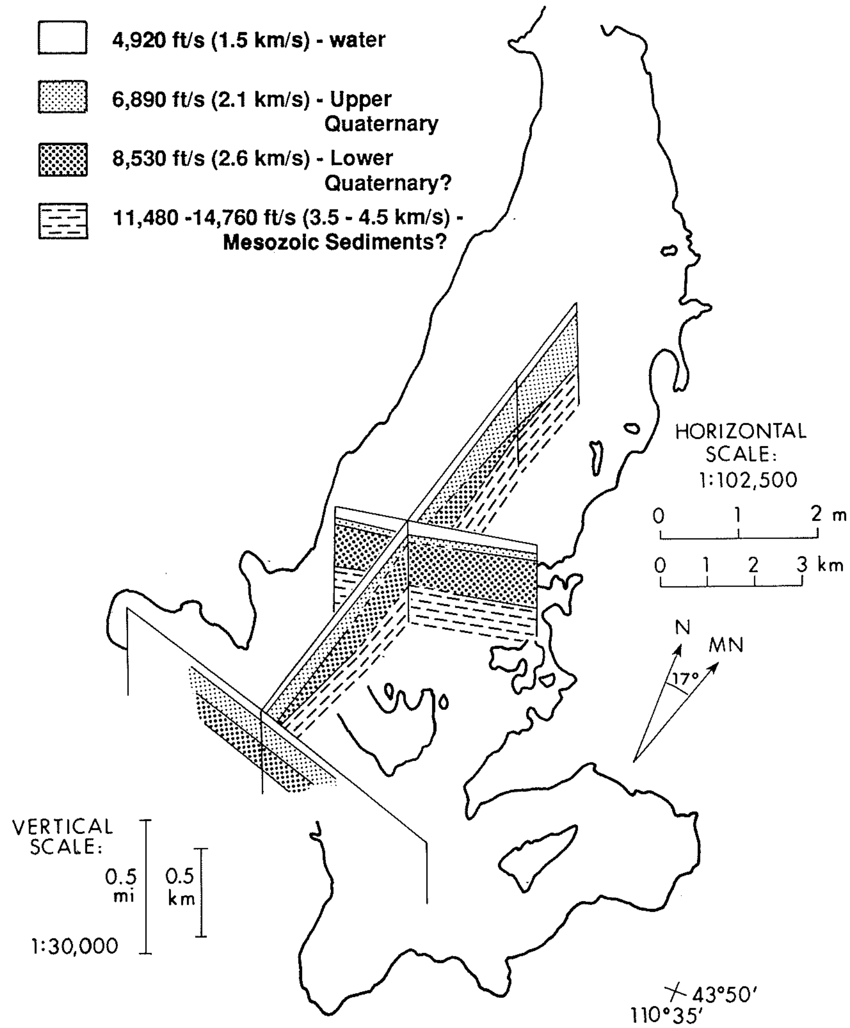

Figure 12. Diagram of the P-wave velocity structure of upper ~ 1,500 ft (0.5 km) of the Jackson Lake basin. Velocities and depths were determined by ray-tracing for one-dimensional models of unreversed refraction lines shown in Figure 11.

Figure 13 shows a detailed refraction/wide-angle reflection profile (corresponding to the location of profile 4, **Figure 11**) re-

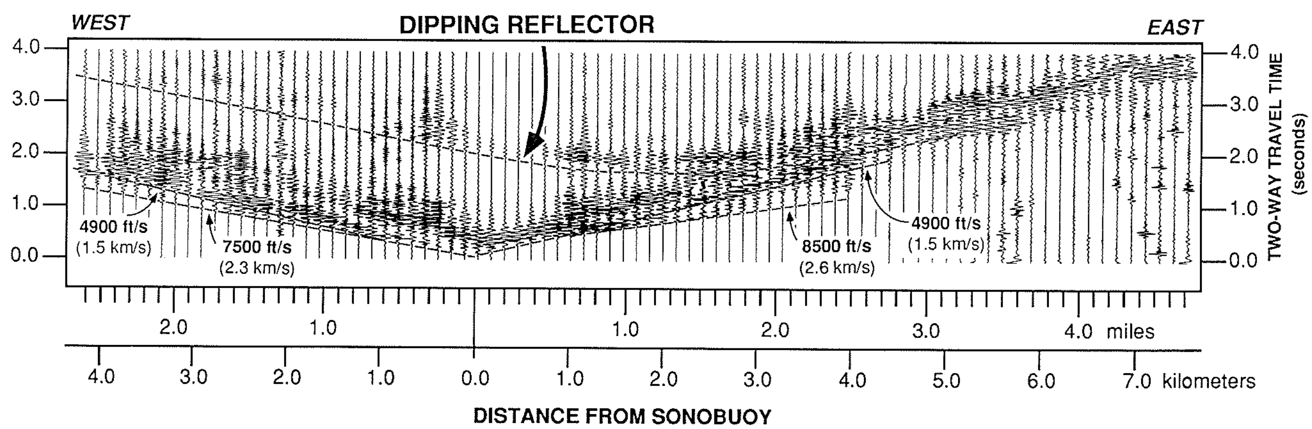

Figure 13. Seismic refraction and wide-angle reflection profile across the south end of Jackson Lake from south of Elk Island to Signal Mountain. Location corresponds to line 4 on Figure 11. A radio-telemetered, single-channel sonobuoy (recorder) was placed southwest of Elk Island and the source was towed east and west to the ends of the profiles.

corded from a fixed air-gun source (southwest of Elk Island) eastward toward Signal Mountain and westward across Moran Bay. The notable arrivals on this profile (**Figure 13**) include a direct wave associated with the water-bottom saturated sediments at a P-wave velocity of 4,757 ft/s (1.45 km/s). A second arrival represents a refractor from a layer that is interpreted to represent shallow lake sediments with a velocity of 6,560 ft/s (2.3 km/s) and an average thickness of 430 ft (130 m).

A secondary arrival on this record section is seen between 2 and 3 seconds two-way time as a hyperbolic travel-time branch and is interpreted to be a wide-angle reflection from a sub-basin or basement layer. Using an averaged velocity of about 9,850 ft/s (3 km/s), estimated from the moveout of this arrival, the top of this reflecting layer (**Figure 13**) is calculated to be about 2.7 mi (4.3 km) below Elk Island and the dip is 42° west.

To examine the relationship of this west dipping reflection, we have constructed a generalized east-west cross section across the southern end of Jackson Lake (**Figure 14**) on the basis of the seismic data shown in **Figure 13** and the projection of on-shore mapped exposures of the 2 Ma Huckleberry Ridge Tuff by Gilbert and others (1983). The projection of the Teton fault, at a postulated eastward dip of 60° (estimated by Smith, Byrd, and Susong, this volume), is also shown.

The dip of the Huckleberry Ridge Tuff in northern Jackson Hole increases westward toward the Teton fault (**Figure 14**). The change in dip with distance from the Teton fault shown in **Figure 14** is taken from dips of the Huckleberry Ridge Tuff mapped by Gilbert and others (1983, figure D-3) around the east and north sides of Jackson Lake. It should be noted, however, that a component of the tilt of these units may be due to local tilting on a small, north-striking down-to-the-east normal fault east of Signal Mountain. The projected position of the Huckleberry Ridge Tuff at a depth of 6,000 ft (1.8 km) beneath Elk Island (dashed line, **Figure 14**) is shallower than the 42° dipping reflector beneath Elk Island (heavy line, **Figure 14**), but these lines intersect between Elk Island and Hermitage Point. If the prominent reflector is Huckleberry Ridge Tuff, it dips much steeper than projected from surface outcrops. It also could be an older layer, such as the 6 to 4.2 Ma tuff exposed on Signal Mountain or the inter-

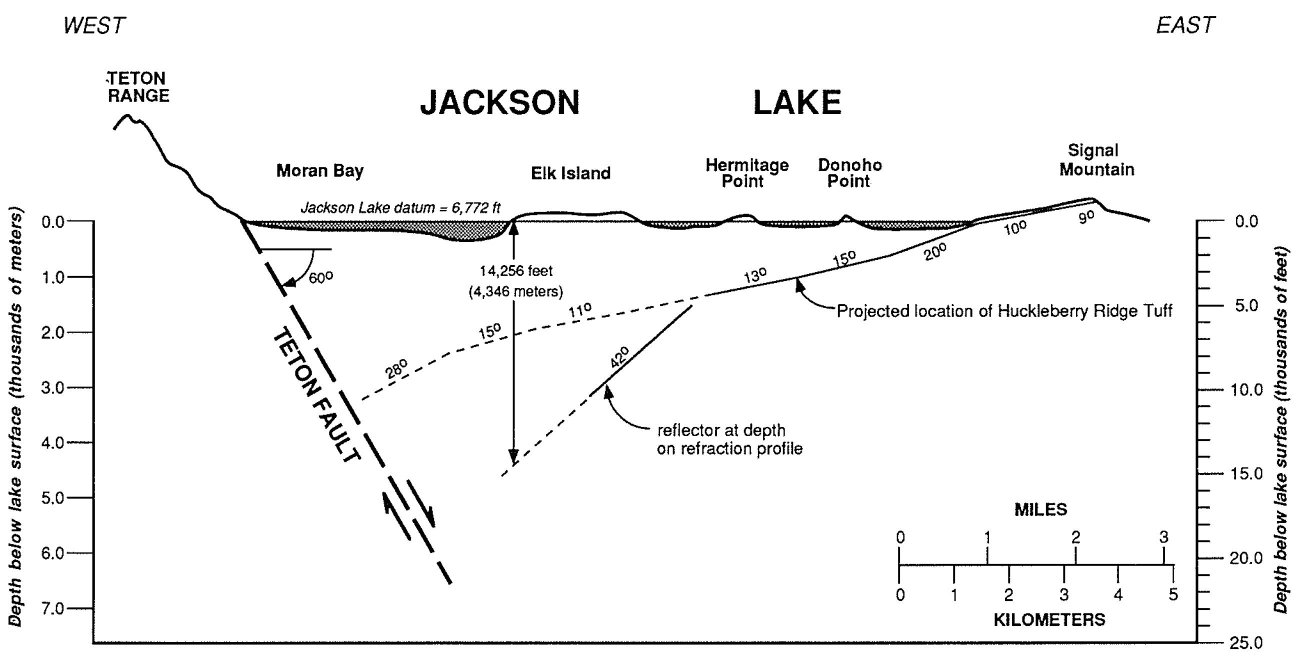

Figure 14. Interpreted geologic east-west cross section of the southern Jackson Lake basin. The profile represents the bathymetry and upper-crustal structure along a generalized east-west line from Moran Bay to Signal Mountain. The cross section shows the projection of the westward-dipping Huckleberry Ridge Tuff (from Gilbert and others, 1983) exposures north of Jackson Lake (dashed lines) and on and near Signal Mountain (solid lines). The projected location of the Teton fault is from Smith, Byrd, and Susong (this volume). Lake depths are exaggerated.

face between much older Mesozoic and Paleozoic consolidated units or Precambrian rocks. Nonetheless, the steeper westward dip of the reflector is consistent with hanging-wall subsidence of the sediments produced by large scarp-forming earthquakes on the Teton fault (see Smith, Byrd, and Susong, this volume, for a detailed example). Note that the westward increase of dip of both the Huckleberry Ridge Tuff and the deep reflector are consistent with a listric geometry for the Teton fault at depth. However, the data are insufficient to confidently determine the fault geometry.

Conclusions

The structure and Quaternary history of Jackson Lake were delineated by seismic reflection and refraction data, paleomagnetic data, and piston cores and integrated with the glacial history of the region. The high-resolution (7.5kHz) seismic reflection data used to determine the bathymetry of Jackson Lake showed a main western trough up to 437 ft (133 m) deep and a separate but shallower trough up to 142 ft deep (43 m) on the east side of the lake. Distinguishable sediment packets were recognized by coherent reflections bounded by notable unconformities, which are interpreted to represent different episodes of glacial and postglacial sedimentation in the lake. The floor of Jackson Lake is underlain by Quaternary deposits marked by angular unconformities and locally interbedded undisturbed and disturbed layers. Sediments recovered from four 6.5- to 12-ft (2 to 4 m) long piston cores in the upper 3 or 4 m of unit A were composed dominantly of silt-sized (4 to 60 mm) diatom frustules mixed with a few percent solid detritus of quartz, feldspar, and mica (Shuey and others, 1977).

Sediments in the upper part of the western (main) basin of Jackson Lake consist of an undisturbed near-surface layer up to 70 ft (23 m) thick interpreted to have been deposited in postglacial time, which includes all of Holocene time (last 10,000 years or more) and a few thousand years of latest Pleistocene time. Deeper units form packets between subhorizontal boundaries, but contain contorted and steeply inclined beds interpreted as slumps of unconsolidated sediment from the Snake River delta. In contrast, the reflection data in the Signal Mountain-Spalding Bay basin show tilted sediment layers with alternately east- and west-dipping units interpreted to indicate primary dips inclined away from glacial sources of sediment to both the northwest and northeast.

Sedimentation rates of Holocene sediments of Jackson Lake, estimated from paleomagnetic determinations of paleoinclinations of piston cores, averaged 0.06 to 0.08 in/yr (0.1 to 0.2 cm/yr) for the past 1,800 years (Shuey and others, 1977). The sedimentation rate for the upper part of this unit (0.15 cm/yr) yields an age of 10 ka for unit A, which is a minimum age because it does not account for sediment compaction with time and depth.

Our interpretations of the seismic data from Jackson Lake correlate well with the glacial history of northern Jackson Hole. Along the southern margin of the greater Yellowstone ice-mass in late Pleistocene time, three glacial lobes pushed into northern Jackson Hole and produced the main features of the Jackson Lake basin by scouring and deposition of sediments, first in a glacial trough on the east side of the lake and then in a larger one to the west. During the first phase (Burned Ridge) of the last glaciation (Pinedale), westward flow of the Pacific Creek glacial lobe (75 ka to 25 ka) scoured the Signal Mountain trough to depths of 600 ft (185 m). During the second and third phases (Hedrick Pond and Jackson Lake) of the last glaciation (40 to 15 ka), southward flow of the Snake River lobe scoured out the deep western trough to a depth of about 800 ft (245 m). This trough was subsequently about half filled with late glacial and postglacial sediment.

We did not identify any significant evidence in the reflection data of faulting within the Quaternary sediments of Jackson Lake or along the projection of the Teton fault zone across the east side of Moran Bay. This finding is substantiated by detailed mapping (Smith, Byrd and Susong, this volume), which has documented that the Quaternary trace of the Teton fault is located onshore at the west side of Moran Bay and farther north to the Snake River delta. The thickening of the postglacial Holocene sediments along the west side of the western lake basin and adjacent to the Teton fault is consistent with either: (1) up to 100 ft (30 m) of hanging-wall subsidence in the last ~10,000 years, or (2) sediment accumulation in that area due to a plume of sediment discharged from the Snake River. It is possible that both mechanisms contributed.

The general characteristics of Jackson Lake basin sedimentation were controlled by late Pleistocene glaciation. However, the seismic profiles do not have sufficient resolution to reveal the gentle tilting of trough-filling sediments toward the Teton fault because of the very small magnitude of the postglacial tilts. These are estimated to be less than 1° based on the simple geometry of < 20 m downthrow from a hinge up to 9.4 mi (15 km) away from the fault. We note that this predicted postglacial tilt is much smaller than the expected primary sedimentary dips of up to several degrees, whereas the older Quaternary(?) sediments, into which these basins were excavated, exhibit dips into the Teton fault that tend to increase with depth and which may be tectonic. This interpretation is consistent with large, scarp-forming, prehistoric earthquakes, $6.5 \leq M_S \leq 7.5$, thought to have dropped the hanging-wall block of the Teton fault several kilometers during the 9 to 6 Ma structural evolution of Jackson Lake (Smith, Byrd, and Susong, this volume).

In northern Jackson Hole, glacial scour during the last glaciation locally removed as much as 800 feet (250 m) of the weakly consolidated sediments, first by excavation of the east-west Signal Mountain trough and then the north-south western basin. We thus interpret that the general evolution of the sedimentary basin in which Jackson Lake is located is the result of localized, hanging-wall subsidence produced by earthquake slip on the Teton fault during the past 5 to 9 m.y. However, the principal evolution of the Jackson Lake sedimentary basin was by glacial scouring of this sediment-filled structural basin and buildup of moraine and outwash embankments on the southern margin of the lake. Following glaciation, Jackson Lake received deposits of relatively undisturbed, silica-rich diatomaceous muds.

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