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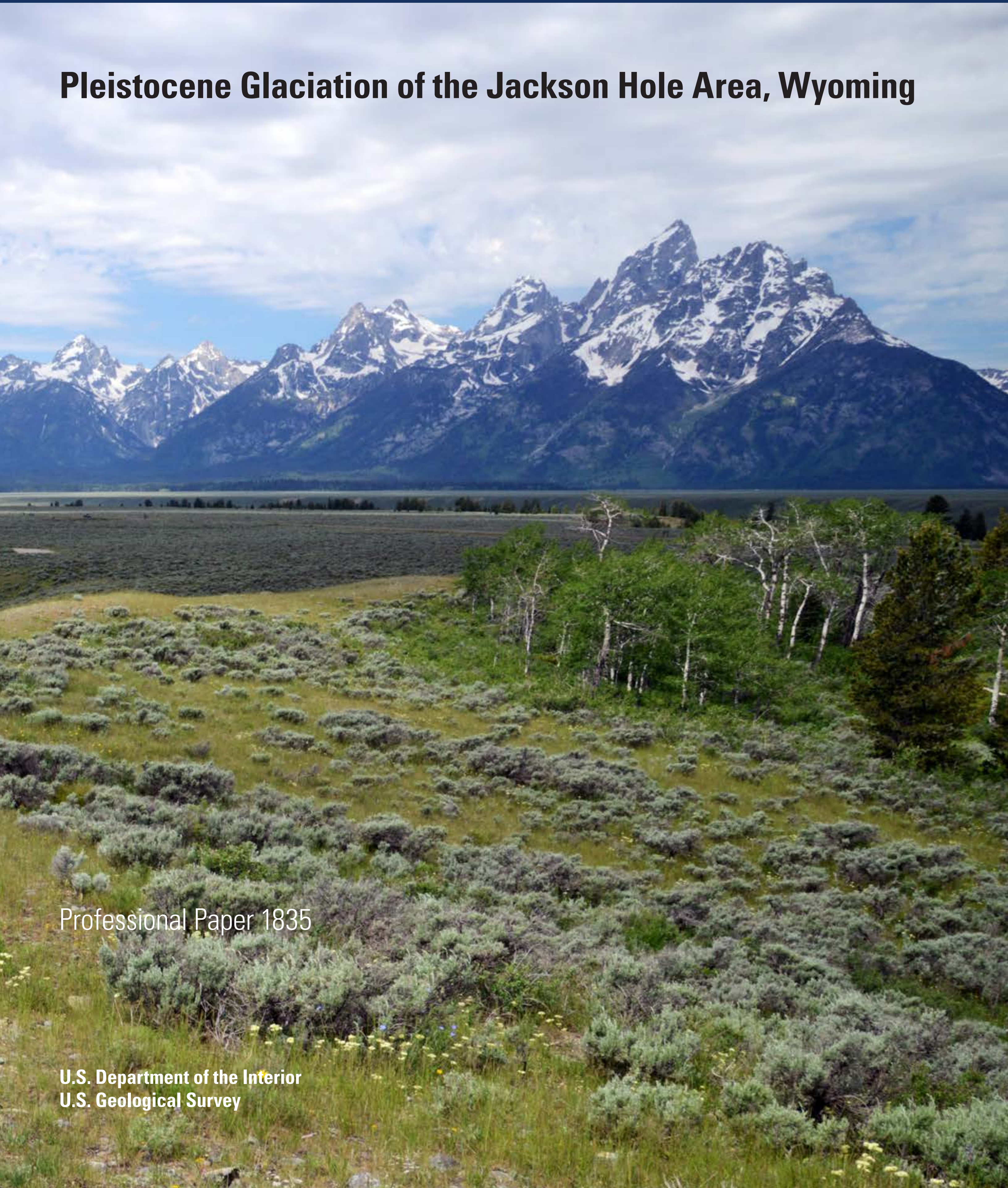
Pleistocene Glaciation of the Jackson Hole Area, Wyoming



Professional Paper 1835

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Cover. Pinedale-1 glacial moraine deposited by the Buffalo Fork lobe of the Greater Yellowstone Glacial System that headed 50 kilometers (30 miles) to the northeast in the high Absaroka Range. The flat surface in the middle distance is the Pinedale-1 outwash terrace. On this side of this flat terrace is a deep glacial kettle formed by the melting of a large block of glacial ice buried in this outwash gravel. The distant bench is on the far side of the Snake River (not visible) and is a Pinedale-2 terrace deposited by outwash from the Yellowstone Plateau ice cap. The Teton Range forms the skyline with Grand Teton the highest peak. Although the Teton Range has dramatic glacial features, the greatest effect on the surficial geology of Jackson Hole was that produced by the large glacial lobes that advanced into Jackson Hole along the southern margin of the Greater Yellowstone Glacial System.

Pleistocene Glaciation of the Jackson Hole Area, Wyoming

By Kenneth L. Pierce, Joseph M. Licciardi, John M. Good, and Cheryl Jaworowski

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Pleistocene Glaciation of the Jackson Hole Area, Wyoming

By Kenneth L. Pierce,[1] Joseph M. Licciardi,[2] John M. Good,[3] Cheryl Jaworowski[4]

Abstract

Pleistocene glaciations and late Cenozoic offset on the Teton fault have played central roles in shaping the scenic landscapes of the Teton Range and Jackson Hole area in Wyoming. The Teton Range harbored a system of mountain-valley glaciers that produced the striking geomorphic features in these mountains. However, the comparatively much larger southern sector of the Greater Yellowstone glacial system (GYGS) is responsible for creating the more expansive glacial landforms and deposits that dominate Jackson Hole. The glacial history is also inextricably associated with the Yellowstone hotspot, which caused two conditions that have fostered extensive glaciation: (1) uplift and consequent cold temperatures in greater Yellowstone; and (2) the lowland track of the hotspot (eastern Snake River Plain) that funneled moisture to the Yellowstone Plateau and the Yellowstone Crescent of High Terrain (YCHT).

The penultimate (Bull Lake) glaciation filled all of Jackson Hole with glacial ice. Granitic boulders on moraines beyond the south end of Jackson Hole have cosmogenic ^{10}Be exposure ages of ~150 thousand years ago (ka) and correlate with Marine Isotope Stage 6. A thick loess mantle subdues the topography of Bull Lake moraines and caps Bull Lake outwash terraces with a reddish buried soil near the base of the loess having a Bk horizon that extends down into the outwash gravel. The Bull Lake glaciation of Jackson Hole extended 48 kilometers (km) farther south than the Pinedale, representing the largest separation of these two glacial positions in the Western United States. The Bull Lake is also more extensive than the Pinedale on the west (22 km) and southwest (23 km) margins of the GYGS but not on the north and east. This pattern is explained by uplift and subsidence on the leading and trailing "bow-wave" of the YCHT, respectively.

During the last (Pinedale) glaciation, mountain-valley glaciers of the Teton Range extended to the western edge of Jackson Hole and built bouldery moraines that commonly enclose lakes. On the southern margin of the GYGS, prominent glacial outwash terraces define three phases of the Pinedale glaciation in Jackson Hole: Pinedale-1 (Pd-1) by Antelope Flats with subdued channel patterns on the east side of Jackson Hole; Pinedale-2 (Pd-2) by a large outwash fan that includes Baseline Flat on the west side of Jackson Hole with well-defined channel patterns; and Pinedale-3 (Pd-3) by The Potholes and other outwash fans farther up the Snake River in central Jackson Hole. During Pinedale glaciation, three glacial lobes of the GYGS fed into Jackson Hole, and the relative importance of these lobes changed dramatically through time. During the Pd-1 glaciation, the eastern Buffalo Fork lobe dominated whereas in Pd-2 and Pd-3 time the northern Snake River lobe dominated. This is consistent with migration of the GYGS center of ice mass westward and southward as glaciers built up towards the moisture source provided by storms moving northeastward up the eastern Snake River Plain. The recession of the eastern Buffalo Fork lobe in Pd-2 and Pd-3 times is consistent with an enlarged ice mass on the Yellowstone Plateau that placed the eastern part of the GYGS in a precipitation or snow shadow.

In Pd-1 time, the Buffalo Fork lobe reached its maximum extent and was joined by the Pacific Creek lobe. This culmination may correlate with the ~21–18 ka ages of moraines in the Teton Range and nearby ranges. Three subdivisions of Pd-1 glaciation built moraines that are nearly or entirely covered by outwash almost 100 meters thick. In Pd-2 time, the Snake River lobe joined with the Pacific Creek lobe and built a large outwash fan south of the present-day Jackson Lake. Boulders on a moraine at the head of this fan are dated to 15.5 ± 0.5 ka. The relation between Teton glaciers and those of the GYGS is indicated by outwash from these Pd-2 moraines that partly buries outer Jenny Lake moraines dated to 15.2 ± 0.7 ka. East of the large outwash fan, Pd-2 ice advanced across the glacial-age Triangle X-2 lake sediments, perhaps in a surge. The Buffalo Fork lobe retreated more than 20 km up valley from its Pd-1 position and Pd-2 ice of the Snake River and Pacific Creek lobes advanced into the area previously occupied by the Buffalo Fork lobe. The Pd-3 position flanks the margin of Jackson Lake and represents a retreat to a stable position after the Pd-2 7-km advance that may have been a surge across the Triangle X-2 lake sediments. The Potholes and South Landing outwash fans were built in the area deglaciated by the retreat from Pd-2 to Pd-3 time. The Spalding Bay outwash fan continued to incise and a meltwater stream flowed just outside the Teton glacier that filled the present Jenny Lake and deposited the 14.4 ± 0.8 ka inner Jenny Lake moraines.

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[4]National Park Service, retired.

Glacial outwash terraces increase in slope toward their respective moraines of the GYGS and are complex in both north-south and east-west directions. The Pd-1 terrace slopes to the west where it is buried by the Pd-2 outwash. The post-depositional tilting of the Pd-1 outwash terrace is an order of magnitude smaller than the original westward depositional slope. The Pd-1, 2, and 3 terraces have a shingle-like geometry such that the highest terrace decreases in age down valley, and in southern Jackson Hole, the Pd-3 terrace is only 3–5 m above the Snake River.

In Pd-1 time the combined Buffalo Fork and Pacific Creek lobes scoured out four basins: (1) Emma Matilda Lake; (2) Two Ocean Lake; (3) a deep basin from lower Pacific Creek to beneath the Oxbows and Jackson Lake Dam; and (4) the largest basin from the lower Buffalo Fork to Deadmans Bar of the Snake River. These basins are largely filled with fine-grained sediment and are now marked by moist lowlands or lakes. In Pd-2 and Pd-3 time the Snake River lobe scoured the present 120-m deep Jackson Lake and possibly the 120-m deeper sediment-filled basin. Subglacial erosion of the Jackson Lake basin by confined water jets is supported by eskers that climb up to the head of the South Landing outwash fan.

Introduction

The remarkable landscapes of Jackson Hole and the surrounding mountains strongly reflect Quaternary geologic processes, particularly those of tectonics and glaciation (fig. 1) (Fryxell, 1938; Foster and others, 2010). The Yellowstone hotspot is fundamental to the dynamics of these processes, for it has produced (1) the Yellowstone Crescent of High Terrain (YCHT), and (2) the lowland hotspot track of the eastern Snake River Plain. Moisture-laden storm systems from the Pacific Ocean, both now and during the Pleistocene ice ages, move far inland along the low-lying Snake River Plain (fig. 2) and then must rise up and over the YCHT, producing deep orographic snowfall in the greater Yellowstone area. The hotspot has also played a dynamic role in the latest Cenozoic offset on the Teton fault, and thus the creation of the Teton Range and Jackson Hole (Pierce and Morgan, 1992; Love and others, 2003).

The landscapes of Jackson Hole are largely an array of glacial deposits and glacial scour features. These include the expansive outwash plains from the last (Pinedale) glaciation and Pinedale glacial scour basins such as Jackson Lake. In southern Jackson Hole, the bedrock ridges of East and West Gros Ventre Buttes were scoured and streamlined during the next-to-last (Bull Lake) glaciation. The Teton Range was sculpted into glacial cirques, serrated ridges, and U-shaped valleys during the last glaciation (Fryxell 1938), as well as during the more than 50 cold intervals that occurred during Quaternary time (the last 2.588 million years) (Gibbard and others, 2009). Although the Teton Range has dramatic glacial features, the greatest effect on the surficial geology of Jackson Hole was that produced by the large glacial lobes that advanced into Jackson Hole along the southern margin of the Greater Yellowstone Glacial System (GYGS) (fig. 1).

Previous Work

Fritiof Fryxell (1930) was the first geologist to conduct a detailed study of the glacial features of Jackson Hole. However, his synthesis of the glacial source areas and succession differs significantly from that presented here. He focused on glaciers from the Tetons (Fryxell, 1938), but was ambiguous about the importance of glaciers entering Jackson Hole from the north as part of the GYGS. His focus on the Tetons is quite understandable, for anyone standing on the floor of Jackson Hole is immediately drawn to the spectacular, high, glaciated Teton Range. In contrast, the broad uplands of mountainous terrain to the northeast and north are distant and less impressive but constitute a much more expansive and potent high glacial source area than the narrow Teton Range. In addition, although Fryxell considered the Burned Ridge moraines to be Bull Lake in age, we find them to be of Pinedale age. Subsequent studies in Jackson Hole by Horberg (1938) and Edmund (1951) followed the Fryxell interpretations. Several reports were published in 1956 as part of an annual field conference held in Jackson Hole, including a review of glacial studies in the region by John de la Montagne (1956), a report by J. David Love (1956) that described four glaciation events in Jackson Hole, and a paper by Love and de la Montagne (1956) concluding that Pleistocene terraces were tilted westward into the Teton fault due to tectonic disturbance within Jackson Hole. E.H. Walker (1964) provided further descriptions of the terraces along the Snake River, particularly down river from Jackson Hole. A north-south transect by Glenn and others (1983) showed that the source of loess in Jackson Hole was probably from the north, as indicated by increasing loess particle size and sand content.

In early versions of the book, “Creation of the Teton Landscape,” Love and Reed (1968) described local late Pleistocene Teton glaciers as well as the large “Buffalo” glaciation from the Beartooth Mountains. A major revision of this book by Love, Reed, and Pierce (2003) added a substantially updated section on the glacial and tectonic history, which was guided by the more recent research of K.L. Pierce. The current report is the scientific documentation for the glacial geology summarized in that book, as well as an update to a U.S. Geological Survey Open-File Report, “Field Guide to the Quaternary Geology of Jackson Hole, Wyoming” by Pierce and Good (1992). The glacial geology is also summarized in Good and Pierce (2015), which is updated from the first printing in 1996.

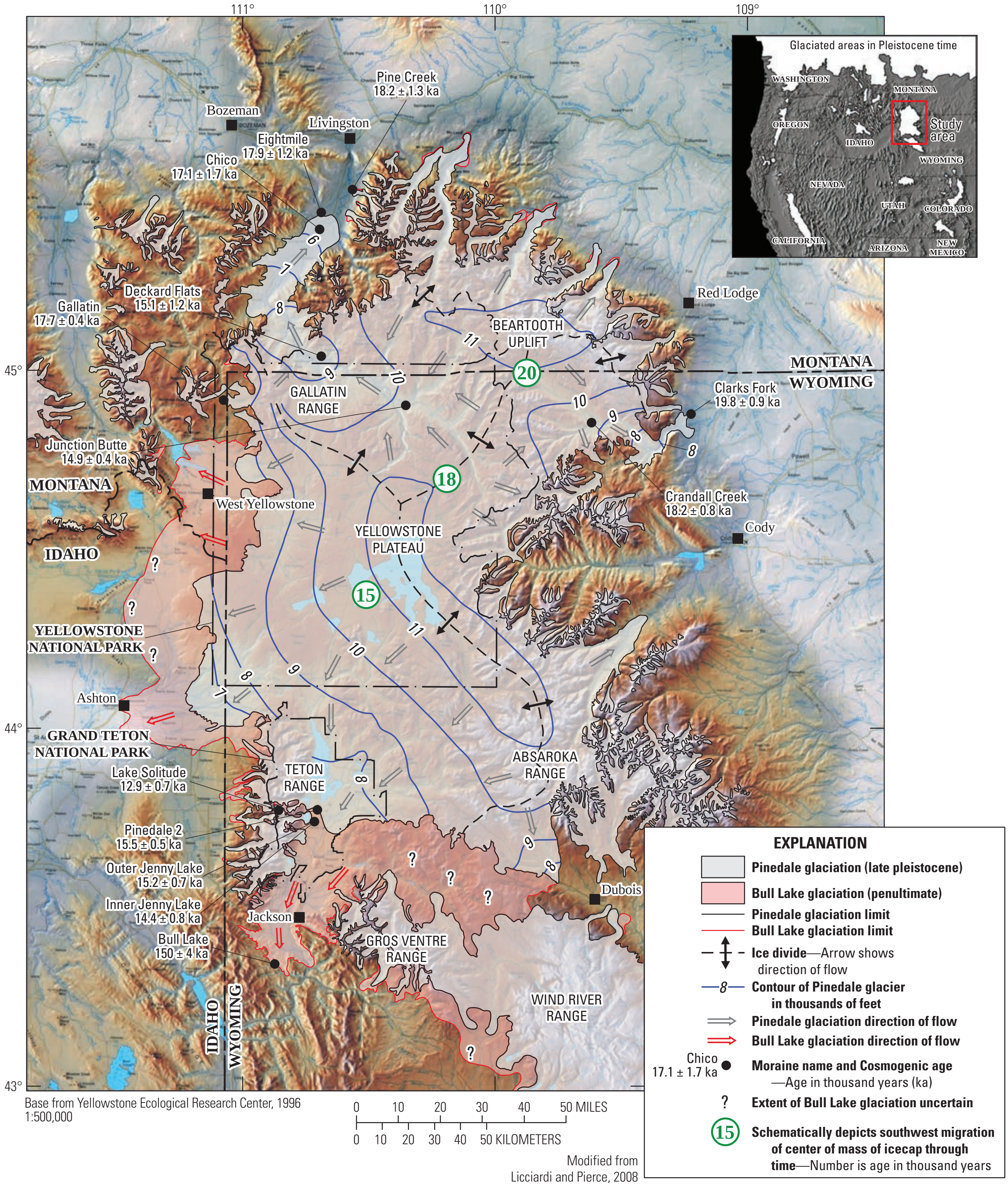


Figure 1. Cosmogenic ages of the Greater Yellowstone Glacial System (GYGS). Ages are in thousands of years based on cosmogenic beryllium-10 dating of glacial boulders. Ages around the periphery of the GYGS are the youngest in Jackson Hole where the Pinedale-2 advance from the Yellowstone Plateau culminated 15.5 ± 0.5 ka.

Geologic Maps

The geologic map of the Grand Teton National Park area (Love and others, 1992, scale 1:62,500) shows the distribution of bedrock formations and glacial deposits (moraine and outwash) for much of the Jackson Hole area. The map unit, “Qg2” of Love and others (1992), includes many of the glacial deposits here assigned to the Bull Lake glaciation. The Love Map Series (LMS) is published by the Wyoming Geological Survey and shows bedrock and surficial geology at a scale of 1:24,000. The 12 LMS maps currently published (LMS-1 to LMS-12) of the 45 total quadrangles are shown in figure 3. The Wyoming Geological Survey continues to publish these maps posthumously as conditions permit. These maps show the character and distribution of surficial deposits, whereas the current report focuses more on the genesis and complex dynamics of the glacial geology.

Geologic Setting: the Yellowstone Hotspot and the Teton Fault

For Jackson Hole and the adjacent mountains, the Yellowstone hotspot (fig. 2) (Pierce and Morgan, 1992; 2009) provides a unifying explanation for the young and ongoing geologic activity such as faulting and uplift, as well as the extensive glaciations that occurred during the Quaternary ice ages As the North American plate has moved at about 25 kilometers (km) per million years (15 miles per million years) to the west-southwest, an inferred relatively stable Yellowstone thermal mantle plume below this moving plate has left a track of volcanism, faulting and uplift that has progressed to the east-northeast (Anders and others, 1989; Pierce and Morgan, 1990, 1992, 2009; Smith and others, 1993a). The ages of the major ash flow tuffs in the volcanic fields are given in million years ago (Ma). Volcanism of the Yellowstone Plateau volcanic field arrived there about 2 million years ago (Christiansen, 2001).

Flaring out from this track like the bow wave of a moving boat is the Yellowstone Crescent of High Terrain (axis shown by dashed red line) and four belts of faulting (I, II, III, IV) that become younger outward from the track of the hotspot. The extensive glaciation of the Greater Yellowstone area, including Jackson Hole, results from two topographic features generated by the Yellowstone hotspot: (1) the Yellowstone Crescent of High Terrain; and (2) the lowland track of the hotspot that serves as a conduit for winter storms that carry Pacific moisture far inland to the Greater Yellowstone area.

The “Major Holocene” faults are shown in darkest black and compose two arms of Belt II (light gray shaded); one that trends west from Yellowstone and another that trends south from Yellowstone and includes the Teton fault.

The formation of the Teton Range and Jackson Hole (fig. 4) is geologically quite young (Love and Reed, 1968; Gilbert and others, 1983; Pierce and Morgan, 1992; Pierce and Good, 1992; Smith and others, 1993a; Anders, 1994; Byrd and others, 1994; Morgan and McIntosh, 2005; Leopold and others, 2007; Morgan and others, 2008). Tilting into the

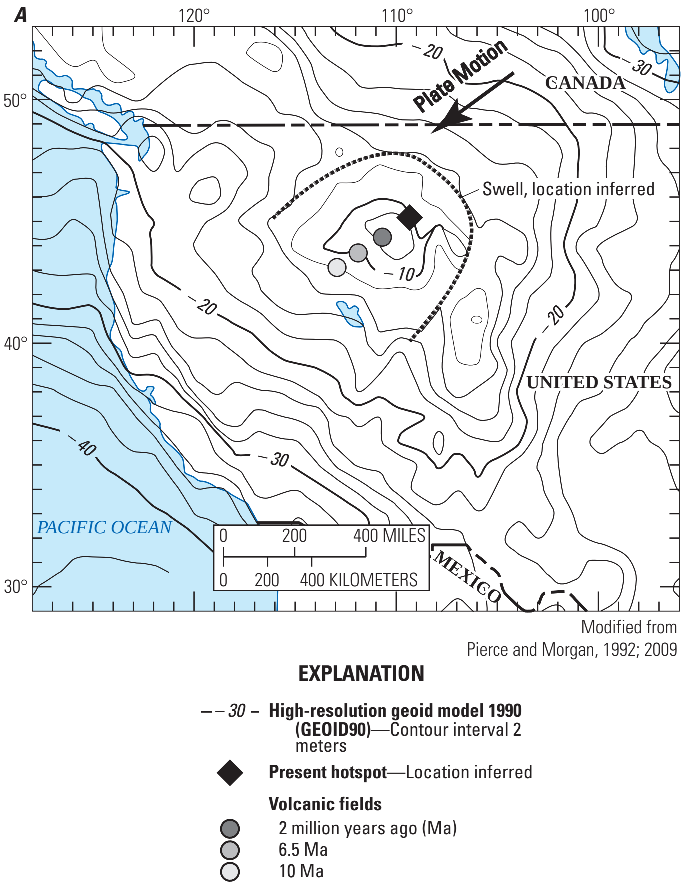
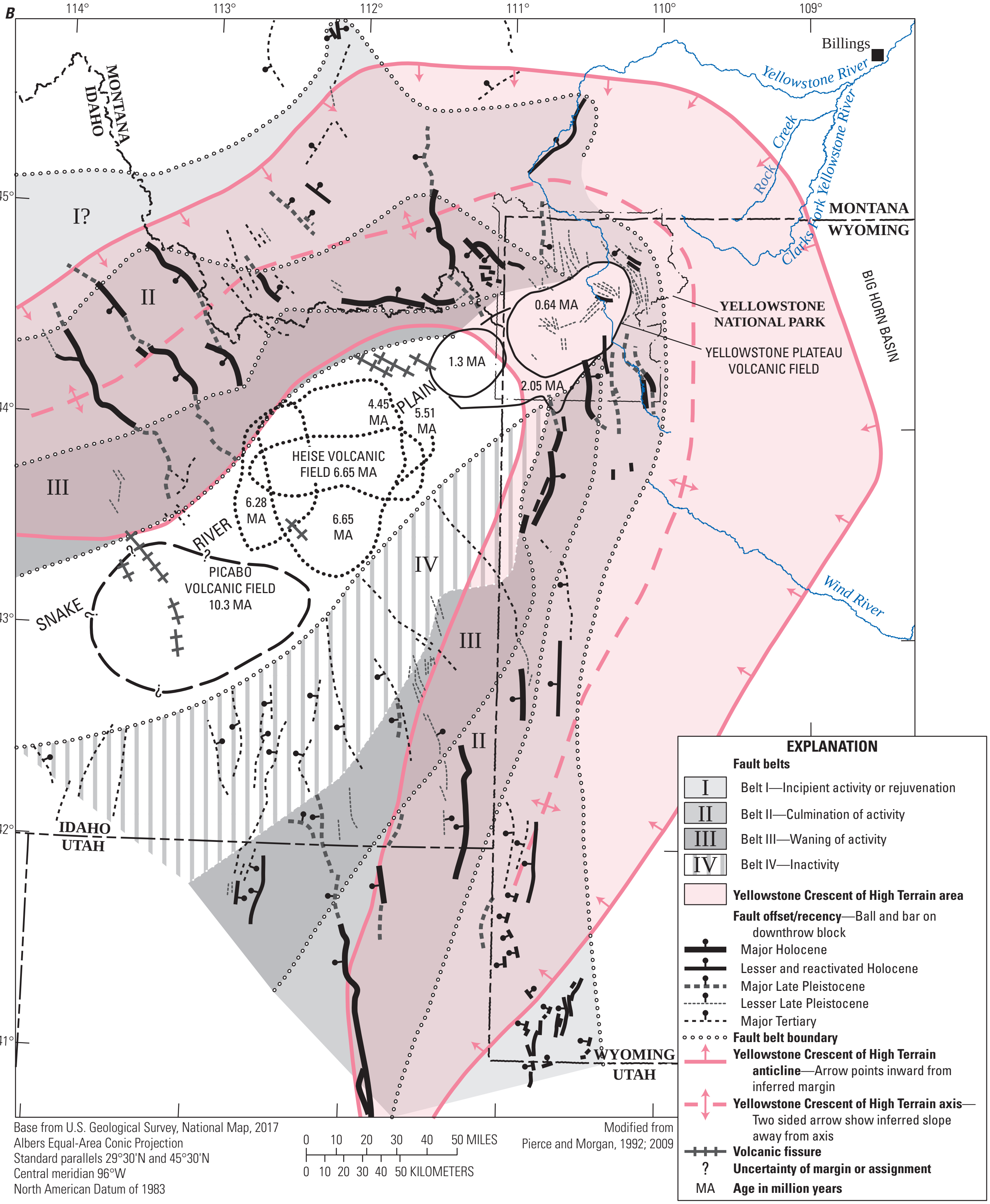


Figure 2. Volcanism, faulting, and uplift associated with the track of the Yellowstone hotspot from 10 Ma to present. The importance of the Yellowstone hotspot to the extensive glaciation of the Greater Yellowstone Glacial System, including Jackson Hole, results from two topographic features generated by the Yellowstone hotspot: *A, T*he geoid of the western United States, volcanic fields along the track of the Yellowstone hotspot, and the inferred swell associated with the hotspot. The track of the Yellowstone hotspot matches in both compass orientation and rate the motion of the North American plate above a thermal plume in the mantle. ; and *B*, the lowland track of the hotspot that serves as a conduit for winter storms that carry Pacific moisture far inland to the Greater Yellowstone area.

Teton fault of originally horizontal volcanic and sedimentary rocks at Signal Mountain (figs. 4 and 5) helps define the late Cenozoic history of the fault (fig. 6). There the Huckleberry Ridge Tuff (2.059 ± 0.004 million years ago [Ma]; Lanphere and others, 2002) is tilted 11° into the Teton fault whereas both the Kilgore Tuff (4.45 ± 0.05 Ma; Morgan and McIntosh, 2005) and the ~10–8 Ma Teewinot Formation dip about 22° into the Teton fault (figs. 5 and 6). This indicates that no tilting occurred between ~10–8 Ma and 4.5 Ma. This pre-faulting interval was followed by two similar rates of tilting from 4.5 Ma to 2.05 Ma and from 2.05 Ma to the present (Pierce and Good, 1992; Pierce and Morgan, 1992, Morgan and others, 2008). Also, the Kilgore Tuff was erupted from the Heise volcanic field (fig. 2B) 100 km west of the Teton Range, whereas



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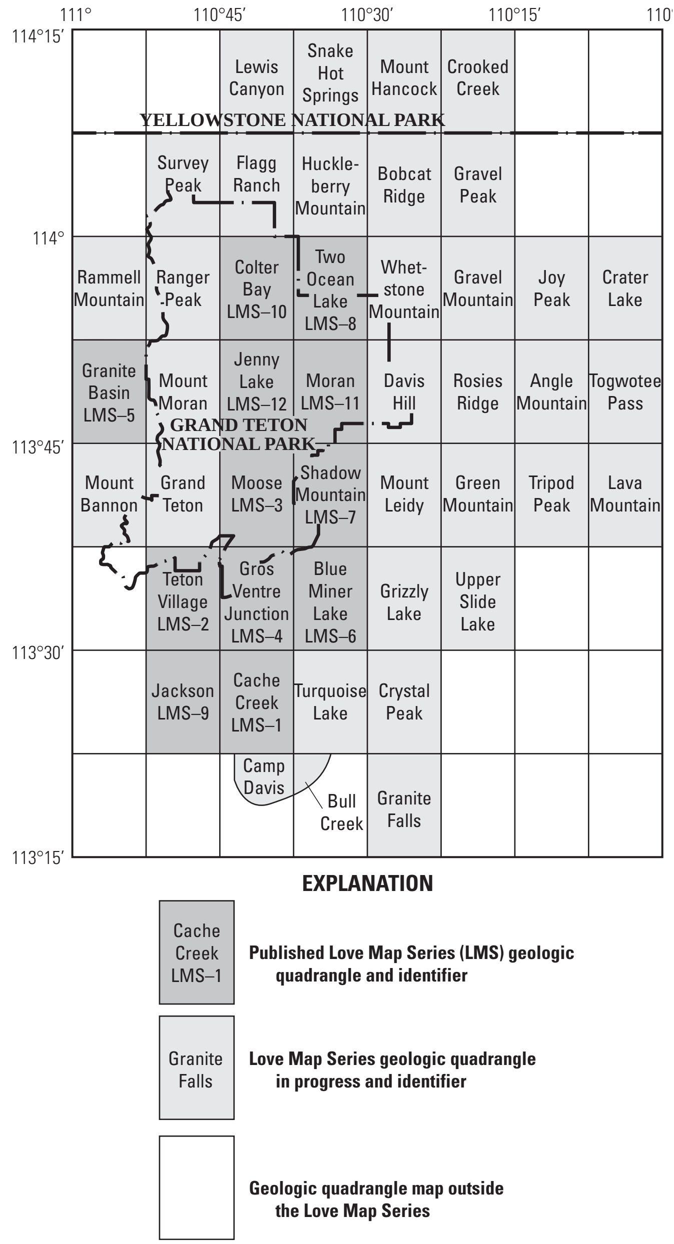


Figure 3. Published geologic maps and maps intended for publication at a scale of 1:24,000 for the Jackson Hole area. Love Map Series (LMS) are geologic maps published by the Wyoming Geological Survey. These maps show both the bedrock and surficial geology. The geologic map of the Grand Teton National Park area (park outline shown by dash-dot line) shows the bedrock and surficial geology at a scale of 1:62,500 (Love and others, 1992).

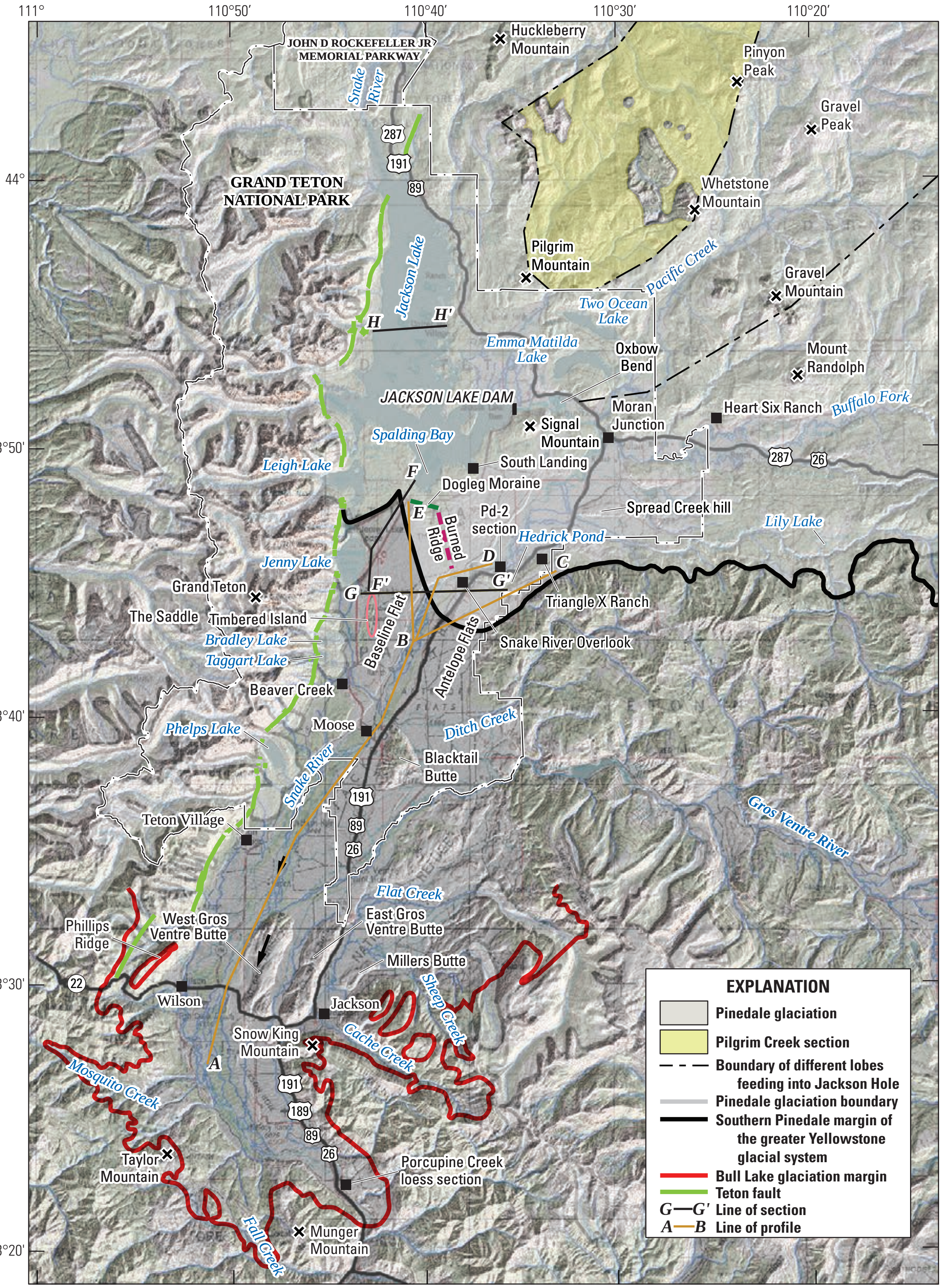
its occurrence on Signal Mountain 15 km east of the range indicates that the Teton Range could not have been a significant topographic feature at the time of emplacement (Morgan and McIntosh, 2005; Morgan and others, 2008). The location, offset, and recency of activity on the Teton fault is documented in studies by Gilbert and others (1983), Smith and others (1990, 1993b), Byrd and others (1994), and Machette and others (2001).

Glacial Geology Overview

The glacial landscapes of the Teton Range are characterized by prominent features including sharp horns, knife-edged ridges, deep cirques, U-shaped valleys, and bulky glacial moraines at the foot of the range (Fryxell, 1938; Foster and others, 2010). However, by far the largest late Pleistocene glaciers and associated outwash streams in Jackson Hole were those along the southern margin of the GYGS (fig. 1) from glacial source areas to the east and north of Jackson Hole. The last glaciation inundated the floor of Jackson Hole with thick glacial outwash gravel and excavated such features as Jackson Lake. About 170–130 thousand years ago (ka), the next-to-last or Bull Lake glaciation, which might be termed the "Jackson whole glaciation," filled all of Jackson Hole with ice and streamlined major elements of the landscape including East and West Gros Ventre Buttes. Analyses of deep-sea marine sediment cores indicate 8 glacial-interglacial oscillations that occurred every ~100,000 years back to about 800 ka, and more than 40 oscillations that occurred about every ~40,000 years from 0.8 Ma back to the start of the Quaternary Period about 2.6 Ma (for example, Rohling and others, 2014). Consequently, the glacial landscapes of the Teton Range and Jackson Hole are likely to have experienced glacial erosion and deposition for many more episodes older than the Bull Lake and Pinedale glaciations. Indeed, the thousands of meters of sedimentary fill in Jackson Hole may in part record and result from a long history of glacial-interglacial oscillations extending at least as far back as the ~2.6 Ma base of the Quaternary Period.

The GYGS (fig. 1) consisted of a system of interconnected glaciers that included ice sourced from the mountains adjacent to the Yellowstone Plateau and eventually on the Yellowstone Plateau itself (Pierce and others, 2014). For glaciers flowing into Jackson Hole from the GYGS, important source areas in the GYGS were, counterclockwise from east: (1) the high Absaroka Range northward from Togwotee Pass that formed the Buffalo Fork lobe, (2) the upper Yellowstone River-Two Ocean Plateau area that formed the Pacific Creek lobe, (3) the Yellowstone Plateau that formed the Snake River lobe (see ahead to fig. 17). Valley glaciers in the northern Teton Range, including those occupying drainages from Leigh Lake to the north, at times joined the Snake River lobe as it flowed south from the Yellowstone Plateau (fig. 4). From Jenny Lake to the south, glaciers from the southern part of

Figure 4 (following page). Jackson Hole area showing Bull Lake and Pinedale ice margins of the Greater Yellowstone Glacial System, and many of the locations discussed in the text. Light shading–Pinedale glaciers of the Greater Yellowstone Glacial System, as well as the Teton Range and other ranges. The Teton fault is from Machette and others (2001). Terrace profiles: *A–B*, *B–C*, *B–D*, and *B–E* are shown in figure 42; *F–F′* is shown in figure 28; and *G–G′* is shown in figure 32. And Jackson Lake seismic profile *H–H′* is shown in figure 43.



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Ashton, Idaho; Montana; Wyoming, 1972, NL 12-11
Driggs, Idaho; Wyoming, 1981, NK 12-2
Universal Transverse Mercator projection, zone 12, meters
North American Datum of 1983 (NAD83)

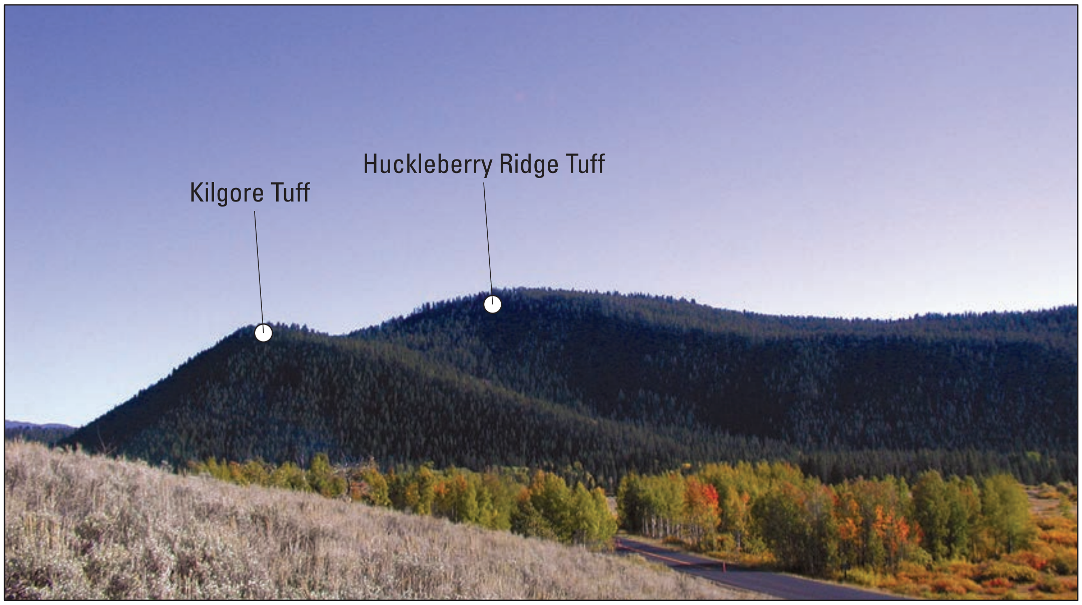


Figure 5. Looking south to Signal Mountain showing tilting to the right into the Teton fault of the Kilgore Tuff and the Huckleberry Ridge Tuff. These volcanic tuffs were close to horizontal when deposited, and now the 4.45 million years ago Kilgore Tuff dips 22° and the 2.06 Ma Huckleberry Ridge Tuff dips 11°. This westward tilt and offset on the Teton normal fault has produced the Jackson Hole and the Teton Range. Photograph by Lisa Morgan, U.S. Geological Survey.

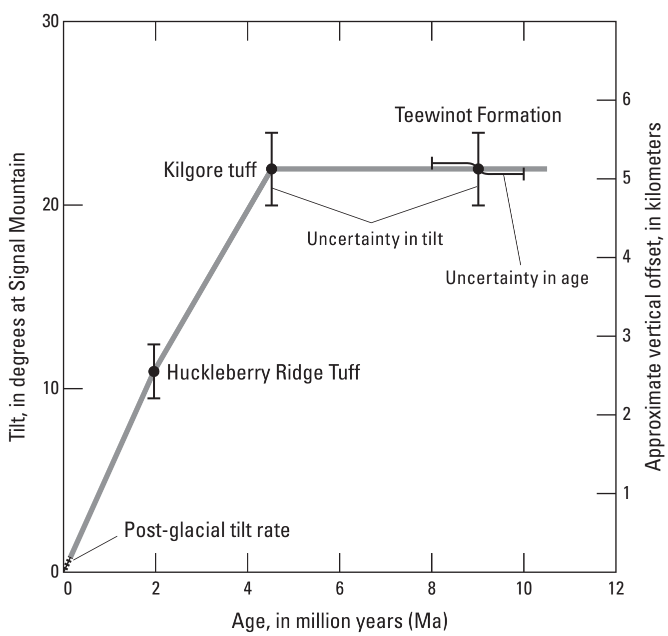


Figure 6. Formation of the Teton Range and Jackson Hole in the last 4.5 Ma based on tilting into the Teton fault of late Cenozoic deposits in the Signal Mountain area.

the Teton Range did not join the GYGS in Pinedale time and constructed moraines on the west side of Jackson Hole at the foot of the range.

Figure 7 outlines the stratigraphic terms used in this report. A roughly equivalent translation of some previous names and designations follows. Love and others (1992) used the letter "g" for drift and moraine debris, and "o" for outwash gravel. Pierce and Good (1992) used the term "Munger glaciation" for the episode now designated as the Bull Lake glaciation because cosmogenic dating by Licciardi and Pierce (2008) confirmed correlation with the type Bull Lake glaciation and Marine Isotope Stage 6 (MIS 6). Many of these Bull Lake deposits had been designated by Love and others (1992) as Qg2 (moraine and till), Qo2 (outwash), Qg3, and locally QTg.

The three recognized phases of the Pinedale glaciation in Jackson Hole, here termed Pinedale-1 (Pd-1), Pinedale-2 (Pd-2), and Pinedale-3 (Pd-3), were previously designated as the Burned Ridge, Hedrick Pond, and Jackson Lake phases by Pierce and Good (1992). Pd-1 deposits were considered to be Bull Lake in age by Fryxell (1930), and Love and others (1992) mapped much of these deposits as Qg4b (moraine and till) and Qo4b ("b" for Burned Ridge). The landform "Burned Ridge" is actually formed of both Pd-1 and Pd-2 age deposits. Love and others (1992) mapped much of what we now consider Pd-2 deposits as Qg4b (till), Qo4b, Qo4j (outwash), and Qg3, and mapped Pd-3 deposits as Qg4j, Qo4j ("j" for Jackson Lake).

The Pleistocene history of the Jackson Hole area reviewed here integrates all available types of geochronologic data, but much of the temporal framework is based on cosmogenic ^{10}Be surface exposure dating of moraine sequences and other glacial features in the region (Licciardi and others, 2001, 2014; Licciardi and Pierce, 2008). All previously obtained cosmogenic ^{10}Be exposure ages discussed in this report are recalculated using a recently developed calibration of regional in situ ^{10}Be production rates based on measurements at

Quaternary stratigraphic terms and ages, Jackson Hole, Wyoming

Age, in thousand years, (ka)	Time divisions	Isotope stages	Glacial moraines of the Greater Yellowstone Glacial System (GYGS)	Outwash deposits	Lakes	Loess and soil development[1]
0	Holocene	1	Little Ice Age 1400–1850 AD Start Neoglaciation ~5 ka		Reservoir, 6,772 feet 1915 + 36 feet dam Jackson Lake 6,736 feet natural	Soil
11.7		11.7 ka				11.7ka
	late Pleistocene	2	Pinedale recession ~12–14 ka Pinedale-3 (Jackson Lake) 14.4 ka Pinedale-2 (Hedrick Pond) 15.5 ka Pinedale-1 (Burned Ridge) 20? ka	Potholes, South Landing Baseline Flat Antelope Flats	Jackson Lake Triangle X-2 (6,800-6,720 feet) Triangle X-1	Loess
		24 ka				25 ka 30 ka Loess 30 ka
		3	smaller glaciations ??			43 ka Loess 51 ka
		59 ka				69 ka
		4	smaller glaciation?	South Blacktail terrace?		Loess
		74 ka				76 ka
		5				Complex of 2 thin loesses and 3 soils
130		130 ka				
	middle Pleistocene	6	Bull Lake, ~ 150 +/- 4 ka (Munger)	Southeast Jackson Hole Timbered Island White Ranch	Beneath Moose to Airport area?	Loess

NOT TO SCALE

[1]Loess and soil development based on Pierce and others (2011)

EXPLANATION

Interglacial or intraglacial interval (beige shading)

Figure 7. Quaternary stratigraphic terms and ages, Jackson Hole area, Wyoming. The names in parentheses are the previous terms used in Pierce and Good (1992). Beige-shaded bands are interglacial or intraglacial intervals. The time scale is not linear. Marine isotope stage boundaries are after Martinson and others (1987).

Promontory Point, Utah (Lifton and others, 2015), which are lower than the globally averaged production rate (Balco and others, 2008) used in our prior work. A nuclide- and time-dependent scaling model formulated by Lifton and others (2014) and designated as "LSDn" is implemented in the age calculations. The recalculated ^{10}Be exposure ages are generally within 1,000 years of those previously published.

Bull Lake Glaciation

The type area of the Bull Lake glaciation is in the Wind River Mountains where it is recognized as the penultimate glacial maximum and hence older than the Pinedale glaciation (Blackwelder, 1915). The age of the Bull Lake glaciation has been controversial and was thought to correlate with the early Wisconsin and MIS 4 (Richmond, 1965). Later, Bull Lake deposits in the West Yellowstone area were dated to about 140 ka (Pierce and others, 1976) and correlated with MIS 6 (fig. 7). Most recently, the type Bull Lake has been dated at about 150 ka (Sharp and others, 2003; Pierce, 2004). The Bull Lake correlates with the (late?) Illinoian glaciation of the midcontental United States (Stiff and Hansel, 2004).

Bull Lake Glaciation Filled Jackson Hole

The Bull Lake glaciation filled all of Jackson Hole with ice, and might be thought of figuratively as the "Jackson whole" glaciation (fig. 8). In Jackson Hole, the Bull Lake glaciation and associated terminal moraines extend 48 km (30 miles) beyond those of Pinedale age (figs. 8 and 9), making this the largest separation of Pinedale and Bull Lake terminal moraines in the Rocky Mountains.

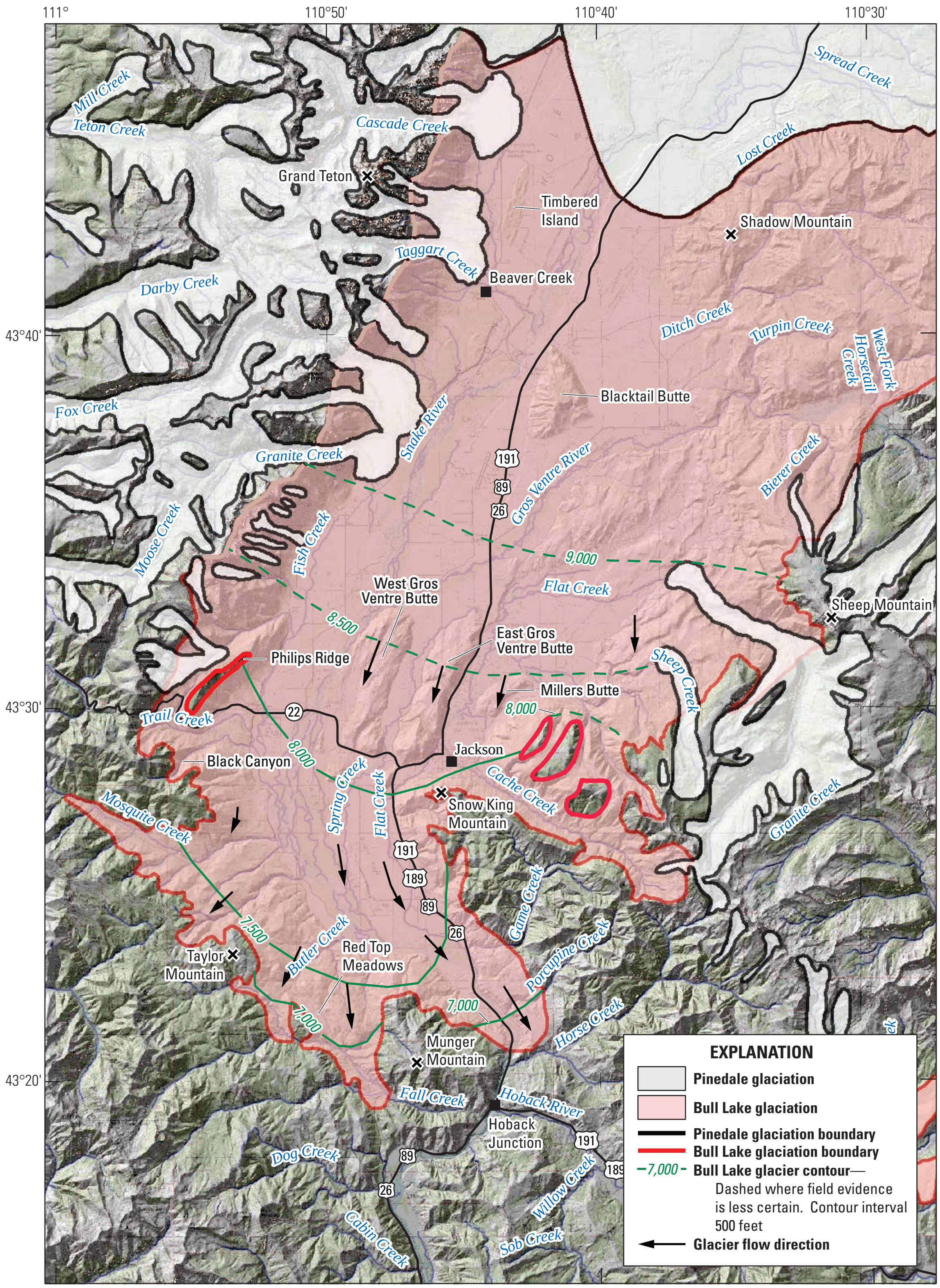
Large boulders on Bull Lake moraines south of Jackson Hole have surface exposure ages that average 133 ± 13 ka, n = 7 (Licciardi and Pierce, 2008). The two oldest ages in the distribution agree within 6 kyr and yield an average of 150 ± 4 ka. Due to concerns over geologic factors that can potentially lead to erroneously young exposure ages on old moraines, such as erosion, exhumation, and past cover, we interpret the average of the two oldest boulder exposure ages as the most reliable age for the Bull Lake deposits (Licciardi and Pierce, 2008). These ages place the Bull Lake moraines in MIS 6 (fig. 7), which spans the interval 190–130 ka (Martinson and others, 1987). Pierce and Good (1992) originally used the local designation "Munger" for these deposits in Jackson Hole because the numerical age in Jackson Hole, as well as the age of the type Bull Lake deposits, were then in doubt. The type Bull Lake outwash (Circle terrace on the east side of the Wind River Range) is now well dated by U-Th ages on soil carbonate coats at about 150 ka, which places the type Bull Lake in MIS 6 (Sharp and others, 2003; see discussion in Pierce, 2004). Additional support for an MIS-6 age comes from a loess-mantled outwash terrace 120 m (400 feet [ft]) above the Snake River in southernmost Jackson Hole. Combined thermal luminescence (TL) ages and soil buildup of meteoric ^{10}Be from atmospheric deposition support an age of 150 ka for the outwash gravel of the glaciation that filled Jackson Hole with ice (Pierce and others, 2011). Bull Lake moraines occur on and adjacent to this terrace that is locally capped with more than 8 m of loess.

The Bull Lake glaciation filled Jackson Hole with ice and near its southern terminus diverged around Munger Mountain to form two lobes (fig. 8). The eastern lobe terminated about 3 km up the Snake River from Hoback Junction whereas the western lobe extended through Red Top Meadows to a terminus along Fall Creek. Observations of the surface altitude of the upper Bull Lake glacier limit, from south to north, include the following (fig. 8): (1) 2,265 m (7,430 ft) on the north slopes of Munger Mountain; (2) 2,380 m (7,800 ft) on Snow King Mountain above Jackson; (3) 2,450 m (8,050 ft) on Phillips Ridge northwest of Wilson; (4) 2,700 m (8,840 ft) south of Flat Creek (North of Jackson Peak); and (5) between 2,930 and 3,050 m (9,600–10,000 ft) on Sheep Mountain (also known as Sleeping Indian). David Adams (oral commun., 1990) suggests that because the Teton fault steps to the west behind Phillips Ridge, Phillips Ridge may be a block sliding into Jackson Hole, which may lower the present altitude of Bull Lake deposits there.

Northward from Sheep Mountain, the height of the Bull Lake glacier continued to increase, covering nearly all the topography on the east side of Jackson Hole. Along the front of the Teton Range northward from Phillips Ridge (altitude 2,450 m; 8,050 ft), the Bull Lake glacier surface also increased in altitude, but only one possible Bull Lake deposit was identified in this rugged, steep terrain on the higher Teton Range. A very bouldery deposit in "The Saddle" (altitude 3,535 m, 11,600 ft) located 900 m southwest of the Grand Teton (fig. 4) has weathering pits on boulders more than 5 centimeters deep which indicate a pre-Pinedale, probable Bull Lake, age.

Glaciers from the Teton Range merged with the western side of the Jackson Hole trunk glacier and carried Proterozoic erratic boulders from the Teton Range southward and into the following valleys (north to south, fig. 8): Trail Creek, Black Canyon, and Mosquito Creek (fig. 10). In the Red Top Meadows area, glaciers sourced from the Teton Range deposited Proterozoic crystalline, quartz-rich boulders suitable for cosmogenic dating (Licciardi and Pierce, 2008).

Figure 8 (following page). Southern extent of Bull Lake glaciation that filled Jackson Hole with ice. North of the 9,000-foot contour, the glacier surface continued to rise towards a Yellowstone source. In addition to the terminus along the Snake River valley, the Bull Lake glacier pushed south between Munger Mountain and Taylor Mountain to its terminus along Fall Creek. Bull Lake glaciation reached as high as the top of Snow King Mountain directly above the town of Jackson as well as near the top of Phillips Ridge on the west side of Jackson Hole. Some of the areas covered by the younger Pinedale glaciation are shown in white. Southerly glacial flow sculpted and streamlined East Gros Ventre Butte, West Gros Ventre Butte and Millers Butte.



Base modified from U.S. Geological Survey digital data, 1:250,000
Driggs, Idaho; Wyoming, 1981, NK 12-2,
Universal Transverse Mercator projection, zone 12, meters
North American Datum of 1983 (NAD83)

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

For many local valley glaciers in the Rocky Mountains, Bull Lake terminal moraine loops typically occur parallel to and about 10 percent farther down valley from the Pinedale moraine loops (Richmond, 1965; Pierce, 2004). Pinedale moraine loops of local glaciers are well represented on the east and west side of Jackson Hole beyond the limit of Pinedale moraines of the GYGS. However, beyond these Pinedale moraine loops, there are no parallel moraine loops of Bull Lake age. For these valley glaciers, either the Pinedale glaciers overrode the Bull Lake moraines, or more logically, the Bull Lake glaciers joined the Bull Lake ice of the GYGS that filled all of Jackson Hole with ice and deposited moraines that are 48 km beyond the Pinedale moraines of the GYGS.

Glacial-scour features from the Bull Lake glaciation in Jackson Hole include East Gros Ventre (fig. 11), West Gros Ventre, and Millers Buttes. All three are bedrock landforms smoothed and streamlined by southward glacial flow.

Bull Lake glacial landforms are well displayed on the grassland slopes on the east side of Jackson Hole south of Flat Creek (fig. 12). Ice marginal channels are eroded as deep as 100 m into bedrock and glacial erratics and glacial moraines occur on the intervening ridges.

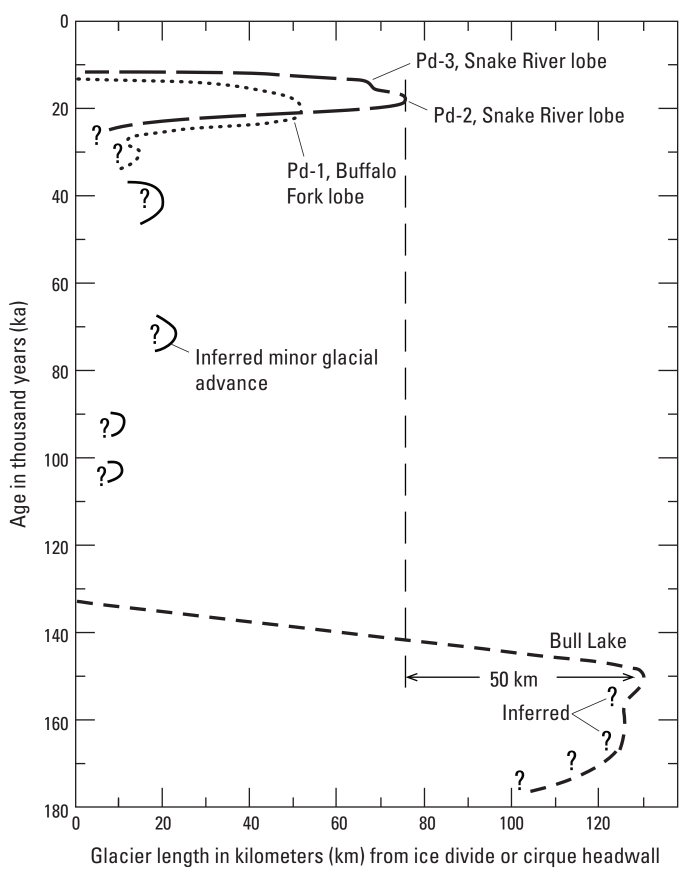


Figure 9. Different lengths of glaciers feeding into Jackson Hole. The Snake River lobe headed above Yellowstone Lake on the Yellowstone Plateau. The minor advances between 110 and 30 ka are based on intervals of loess deposition inferred by Pierce and others (2011) to be associated with glacial advances.

Bull Lake Recessional Deposits

In Jackson Hole, recessional moraines and gravel benches, such as those at Timbered Island and south of Beaver Creek (figs. 4 and 8), occur as much as 40 km (25 miles) up valley from the Bull Lake terminal moraines and might be considered significantly younger than the Bull Lake maximum. Both the terminal area and recessional deposits are generally recognized by a capping of loess having a weakly developed surface soil, but with a well-developed buried soil near the base of the loess with a textural B horizon that is thicker, more clay-rich, and redder than the surface soil. In addition, no evidence of a distinct advance separable in time by end moraine loops and outwash is found associated with these recessional deposits. Taken together, these soil and map relations suggest that the extensive outer Bull Lake deposits and the recessional deposits are associated with the same glaciation.

At Timbered Island (figs. 4 and 8), till fabric analyses indicate deposition by a glacier moving to the southwest (Harrington, 1985). The large Proterozoic boulders on the moraine on the north end of Timbered Island are derived from the Tetons to the west, whereas the quartzite cobbles near the south end are from the northeast, indicating bidirectional deposition from the east and west.

South of Beaver Creek (figs. 4 and 8), Bull Lake deposits include a forested terrace that appears to be tilted into the Teton fault, instead of descending down valley. Over a distance of 1.5 km, the terrace has a negative slope to the south of about 6 m (20 ft), whereas it should have a positive slope of about 15 meters per kilometer (m/km) (55 feet per mile [ft/mi]). This suggests a tilting of about 21 m over a distance of 1.5 km, or 14 m/km over a time span of 150,000 years, which translates

Figure 10. Large glacial erratic above Mosquito Creek in southern Jackson Hole. This granitic rock from the Proterozoic core of the Teton Range was carried ~40 kilometers to the south by Bull Lake glacial flow. This erratic was deposited on Cretaceous shale 215 meters above the valley floor as the Bull Lake glacier receded. Scale is provided by teenage Jennifer Pierce with Standard Poodle, Cricket.

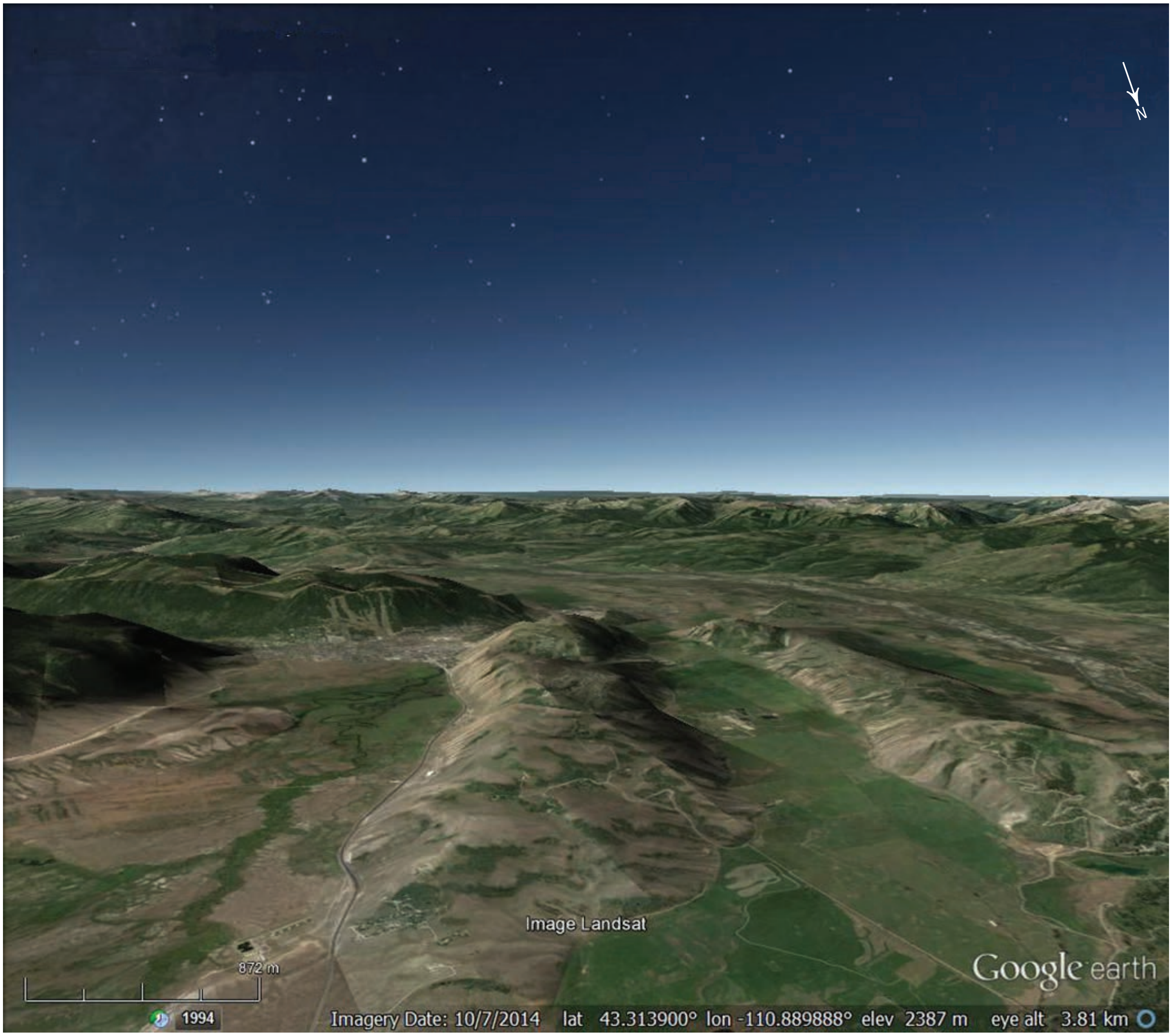


Figure 11. East Gros Ventre Butte in center of image streamlined by Bull Lake glacial flow to south (away from viewer). The town of Jackson is at the left end of the butte and the Bull Lake glacier was thick enough to reach the top of Snow King Mountain directly above the town. Also streamlined by southward glacial flow are West Gros Ventre Butte on the right side of image and the much smaller Millers Butte on the left side of image. Image from Google Earth looking south.

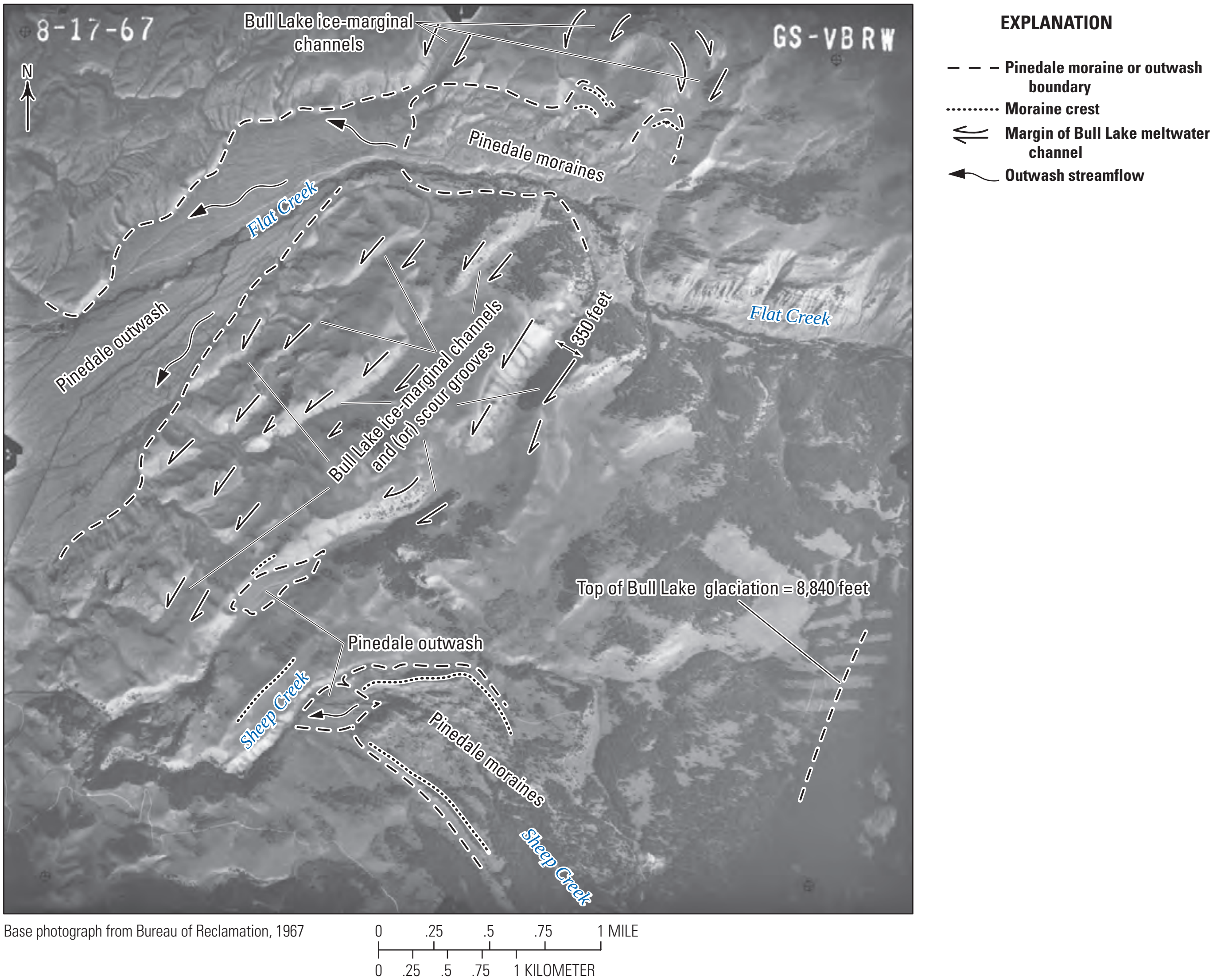


Figure 12. Bull Lake glacial landforms of moraines, meltwater channels, and scour features in meadowlands on the east side of Jackson Hole. The Bull Lake glacier here reached an altitude of ~2,695 meters (8,840 feet) and was about 700 meters thick (2,400 feet) above the floor of Jackson Hole. Along the margin of this receding glacier, lateral moraines were deposited and ice-marginal channels were eroded. This degree of preservation of Bull Lake glacial features is consistent with an age of ~150 ka.

to 0.09 meters per kilometer per thousand years (m/km/ka). As discussed later, this estimated tilting rate of 0.09 m/km/ka since Bull Lake time is similar, given the rough estimates involved, to the estimated basin-wide tilting rate of 0.05 m/km/ka since Pinedale time.

Bull Lake Glaciation in Gros Ventre River Valley (Leidy Formation)

In the Gros Ventre valley (fig. 4), there are remnants of pre-Pinedale glacial deposits of till, outwash, and lake sediments (Lagas, 1984; Love and others, 1992; Love, 1994). Love (1994) named the Leidy Formation for this Pleistocene glaciofluvial-lacustrine sequence of sedimentary deposits. We infer a Bull Lake age for these deposits because: (1) damming of the valley to create a lake in Bull Lake time must have occurred because the Jackson Hole glacier of Bull Lake age blocked the valley of the Gros Ventre River to well above an altitude of 2,750 m (9,000 ft); (2) lake sediments and glaciofluvial sediments are intermixed with Bull Lake till at the mouth of the Gros Ventre valley; and (3) the Leidy Formation is the next older sedimentary deposit than the clear Pinedale moraine loops deposited by valley glaciers in the main Gros Ventre River drainage and its tributaries, and thus is consistent with the geomorphic sequence of Bull Lake followed by Pinedale. Deposits in the lower (western) part of the Gros Ventre valley are rich in Pinyon-type quartzite, indicating the Jackson Hole glacier pushed up the valley more than 11 km (7 miles). Pinyon-type quartzite occurs as densely cemented quartzite roundstones derived from the Pinyon Conglomerate as well as the Hominy Sandstone. About 38 km up the Gros Ventre valley, the Leidy Formation includes giant granitic erratics in till, indicating a glacier source from the Wind River Range (fig. 1) (Love, 1994, p. D10). Lake sediments and glaciofluvial sand and gravel occur both above and below glacial till in both the upper and lower reaches of the Gros Ventre valley; this indicates: (1) blockage of the valley and lacustrine sedimentation; (2) invasion of both the upper and lower ends of the valley by glacial ice; and (3) glacial recession and blockage of the lower end of the valley resulting in accumulation of lake sediments and glaciofluvial sediments.

Some evidence supports the filling of the entire Gros Ventre valley (fig. 4) with Bull Lake ice between the Jackson Hole glacier (fig. 8) and the large Green River glacier of the northern Wind River Range (fig. 1). Possible evidence of glaciation filling to such high altitudes was an observation made by J. David Love (oral commun., ~1990) of erratics of Absaroka volcanics, Pinyon-type quartzite, and Proterozoic crystalline rocks all co-occurring in Packsaddle Pass (altitude 3,080 m; 10,100 ft) 1.5 km south of Pyramid Peak.

Bull Lake Moraines Peripheral to Greater Yellowstone Glacial System

Around the perimeter of the GYGS (fig. 1), Bull Lake glaciers extended 23 km beyond those of the Pinedale glaciation on the southwest near Ashton, Idaho (Colman and Pierce, 1981; Scott, 1982; Pierce and others, 2014), and 22 km beyond those of the Pinedale to the west near West Yellowstone, Montana (Pierce and others, 1976). However, Bull Lake moraines were either overridden or occur only laterally above or slightly beyond Pinedale moraines on the northern and eastern margins of the GYGS (fig. 1).

Southwest of Togwotee Mountain Lodge, moraines with muted topographic expression are offset 20 m (70 ft) by a fault (lat 43.7994 N, long 110.229 W). This fault offset is several times greater than offset of Pinedale moraines and thus supports an older than Pinedale, probable Bull Lake age.

Farther east in the Togwotee Pass-Union Pass area in Bull Lake time, glaciers from the Absaroka Range probably joined glaciers from the northern Wind River Range. Northwest of Dubois, Wyoming (fig. 1), along Warm Spring Creek are older, eroded, and subdued moraines that are down valley from hummocky Pinedale moraines that contain abundant ponds and undrained depressions. These moraines are high above the Wind River, and exhibit basalt-weathering rinds at least 1 millimeter thick. They are thus most likely of Bull Lake age.

Possible Bull Lake-Pinedale Lake Sediments

Glaciers commonly excavate a lake basin upstream from their terminus, especially if they are moving across unconsolidated sediments. Two examples of such glacially excavated lake basins are Jackson Lake of Jackson Hole and Fremont Lake of the Wind River Range. If there was a lake basin excavated by the large Bull Lake glaciation, it would be represented by lake sediments of later Bull Lake age, the Bull Lake-Pinedale interglacial age, and possibly earlier Pinedale age. Such lake sediments are probably now buried by outwash gravels of the Pinedale glaciation.

In a cross section of Jackson Hole, Cox (1974) shows in his figure 7 extensive “lacustrine deposits” buried by “glacial outwash and alluvial deposits.” Water wells in the southern part of Grand Teton National Park commonly encounter fine grained, non-gravelly sediment at depths of 50–100 ft (Cox, 1974). A water well 1 km northeast of Moose (fig. 4) records 82 ft of fine sediment beneath river gravels. A well for the Jackson Hole Airport bottomed in 4 feet of sand overlain by 76 feet of gravel. Eight resistivity soundings using the time-domain electromagnetic method did not encounter low-resistivity sediments in the upper few hundred feet on the floor of Jackson Hole, but one sounding did find shallow, low-resistivity material (40 ohm-meter) near the Moosehead Ranch (fig. 4), 3 km northeast of Triangle X Ranch along Spread Creek (Nolan and Miller, 1995).

Several observations suggest fine-grained sediment of possible Bull Lake lacustrine origin may be present beneath Pinedale gravels in the area between Moose and the Jackson Hole Airport area. Field notes by K.L. Pierce (September 22, 1995) on USGS resistivity soundings in this area indicate low-resistivity material signifying probable lake sediments beneath Pinedale gravels. At the northwest corner of the Jackson Hole Airport boundary, resistivity site #2 displayed 10 ohm-meter material (probable lake sediment) beneath 30 m (100 ft) of high-resistivity material considered to be Pinedale gravel. Three kilometers north of this, resistivity sounding #4 found less than 100 ohm-meter material at ~30 m (100 ft). A kilometer north of Moose, resistivity sounding #3 found high-resistivity gravel over low-resistivity sediment. Lake sediments were observed in the bank of the Snake River near the south end of this sounding. In the area of this sounding, a well encountered the following (in feet): sand, 40–65; clay, 65–85; sand, 85–90; and clay, 90–100.

Pinedale Glaciation

The type Pinedale glaciation is on the west side of the Wind River Range (Blackwelder, 1915; Richmond, 1987) and is of late Pleistocene age (Gosse and others, 1995). We first discuss the relatively small valley glaciers in the mountains adjacent to Jackson Hole, and then discuss the much larger glaciers that advanced into Jackson Hole along the southern margin of the GYGS.

Early (?) Pinedale Terrace

East of the Jackson Hole Airport is a loess-mantled, west-sloping gravel terrace of the Gros Ventre River (fig. 13; Walker, 1964; Love and others, 1992). A soil pit encountered about 3 m of loess and because no buried soil was recognized at the base of the loess, this deposit is considered younger than the Bull Lake glaciation. However, the thickness of the loess mantle indicates this is likely the oldest early Pinedale deposit recognized in Jackson Hole. The scarp forming the west boundary of this terrace has been mapped as a fault scarp (Love and others, 1992), but as discussed in the Pinedale-3 section, this scarp is more likely to have been eroded by Pd-3 floods.

Pinedale Glaciers Apart from the Greater Yellowstone Glacial System

Valley Glaciers on the East Side of the Teton Range

Although the Teton Range is high, it is quite narrow and only a relatively small area rose above the Pleistocene snowline. Thus, its glaciers were of modest size and only 3–13 km long. In the Teton Range south of the GYGS, mountain-valley glaciers formed in glacial cirques and advanced across the precipitous, fault-bounded range front to deposit moraines along the western margin of Jackson Hole (figs. 14 and 15) (Fryxell, 1930; Love and others, 1992). On the broader west side of the Teton Range, some of the Pinedale glaciers were as long as 18 km (Horberg, 1938; Edmund, 1951). These local Teton glaciers were only a small fraction of the size of the GYGS, which had glacial flow paths as long as 140 km (Pierce, 1979). In the terminal moraine area of some local glaciers, four to more than six individual moraine crests can be identified. We describe some of the moraines of these Pinedale glaciers starting with the Jenny Lake glacier and proceeding south from there. The ages of many of these valley glacier moraine complexes have been determined from cosmogenic ^{10}Be dating (Licciardi and Pierce, 2008; Licciardi and others, 2014) (fig. 15).

Jenny Lake Moraines

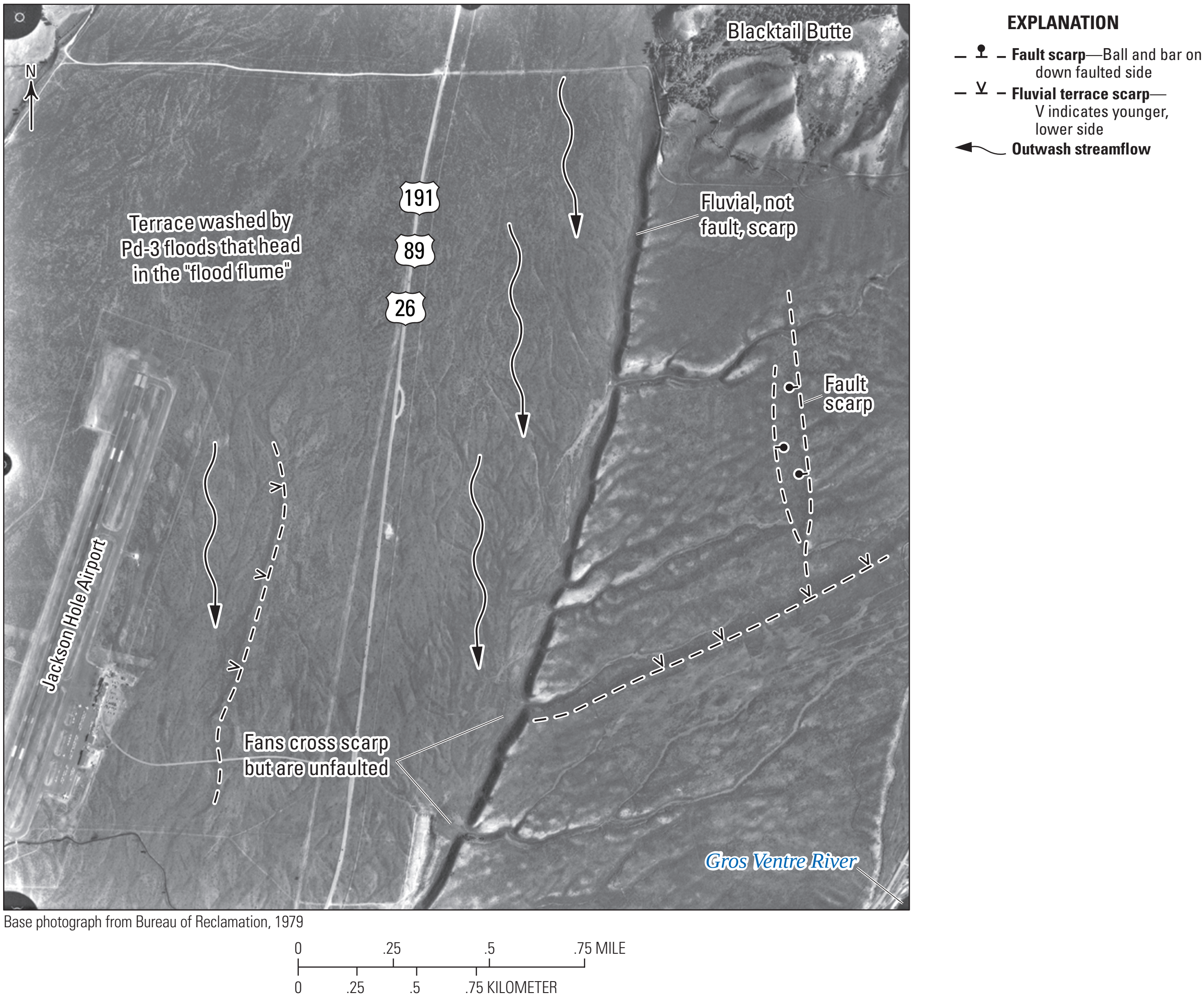
The Cascade Canyon glacier, with its Pinedale terminus defined by the Jenny Lake end moraines, came within 3.5 km of joining the Snake River lobe of the GYGS. The Jenny Lake moraines have an egg-shaped north-south elongation, and enclose the ~73-m deep Jenny Lake (Larson and others, 2016). The outer Jenny Lake moraines are exposed on the east side of the moraine loop but become buried by glacial outwash to the north and south of this exposed segment. The outer Jenny Lake moraines include very large boulders that yield an average age of 15.2 ± 0.7 ka (fig. 15). To the north, these moraines become buried by Pinedale-2 (Pd-2) outwash of the GYGS, indicating the Pd-2 phase of the GYGS is sequentially younger than 15.2 ± 0.7 ka. The inner, recessional Jenny Lake moraines enclose Jenny Lake and have about 5 crests; 7 boulders yield an average age of 14.4 ± 0.8 ka (fig. 15). The glacier depositing the inner moraines filled Jenny Lake at the time when the Pinedale-3b outwash of the GYGS flowed in a trench just outside the inner moraines. The timing of moraine abandonment and ice withdrawal from the Jenny Lake basin, as indicated by the 14.4 ± 0.8 ka age of the inner Jenny Lake moraines, is consistent with the basal-most radiocarbon ages of sediments cored from the bottom of Jenny Lake that lake “sediment accumulation began centuries before 13.8 ka” (Larsen and others, 2016, p. 70). Following deposition of the inner Jenny Lake moraines, upvalley recession was rapid, as revealed by glacial boulders on the bedrock threshold of Lake Solitude near the valley head that date to 12.9 ± 0.7 ka, n = 3 (fig. 15). This indicates that glacial recession of 11.5 km from the inner end moraines to the cirque lip occurred in about 1,500 years, for an average rate of roughly 8 meters per year.

Glacier Gulch Moraines

A succession of bulky lateral and end moraines is located at the foot of the Teton Range down valley from Glacier Gulch which is a glaciated drainage just south of Cascade Canyon and Jenny Lake (fig. 15). The Glacier Gulch moraines do not enclose a lake at present, but low-relief meadows and bogs inside the terminal moraine attest to post-glacial sediment accumulation in the wake of ice retreat from the terminal area. Boulders from the Glacier Gulch terminal moraines have an average exposure age of 15.9 ± 0.9 ka (n = 4).

Bradley Lake and Taggart Lake Moraines

Bradley and Taggart end and lateral moraines abut on their adjacent side, and each encloses small lakes (fig. 4). The end moraines rise to about 100 m (300 ft) above the valley floor. The outer (distal) zone of the Taggart end moraine complex is dated to 15.4 ± 0.6 ka (n = 4), and the average exposure age of 2 boulders on the inner (proximal) portion of the moraines is 14.9 ± 0.3 ka, not including two young outliers (fig. 15). The large boulder pictured in figure 16 yielded an exposure age of 15.2 ± 0.3 ka and fire-spalling did not affect the sample dated. The right lateral Taggart Lake moraine is offset by two strands of the Teton fault about 320 m apart. The upper scarp has vertical surface offset of 9 m and apparent left lateral offset of 9.8 ± 2 m.



Base photograph from Bureau of Reclamation, 1979

Figure 13. Low sun-angle aerial photograph showing loess-mantled, early Pinedale terrace trimmed back by Pinedale-3 floods east of the Jackson Hole Airport. Terrace on the right side of photograph was deposited by Gros Ventre River in earlier Pinedale time and has channel flow patterns and surface slope to the southwest. Although Bull Lake deposits typically exhibit a buried soil spanning the loess-gravel contact, this deposit does not, and is therefore suggested to be of earlier Pinedale age. Note the small fault scarp with an antithetical scarp shown on the loess-mantled terrace but no similar antithetic fault occurs on the prominent scarp. The prominent scarp has been interpreted to be a fault scarp (Love and others, 1992) but is here interpreted to be a fluvial scarp undercut by Pd-3 floods. The small alluvial fans at the base of the scarp exhibit no evidence of faulting and no fault scarp extends into Pinedale terrace gravels of the Gros Ventre River beyond the southern end of the scarp (south of this photograph).

Figure 14. Pinedale moraines of the Teton Range south of and separate from the Greater Yellowstone Glacial System. The moraines are marked by irregular, partly forested lobate ridges that commonly encircle lakes. The lakes, from left to right, are: Taggart (near center of the picture), Bradley, Jenny, Leigh, and part of Jackson Lake. The glaciers that flowed out of the Tetons were small compared to the great ice lobes that flowed into Jackson Hole from the Greater Yellowstone Glacial System. Oblique color aerial photograph by Michael Collier of Flagstaff, Arizona.

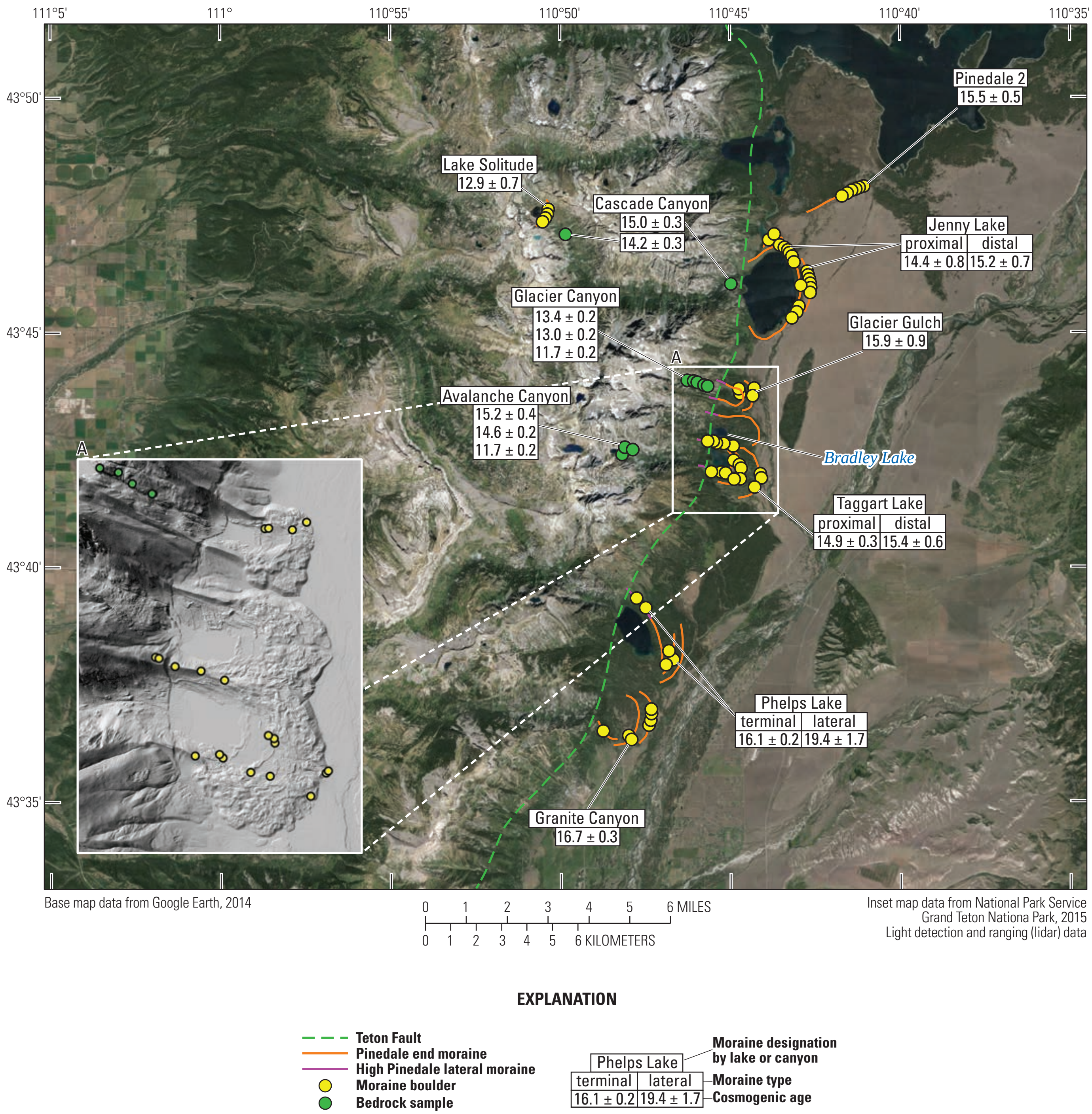


Figure 15. Beryllium-10 ages of lateral and end moraines deposited by glaciers from the Teton Range and glacially scoured bedrock of the Teton Range. The end moraines commonly date several thousand years younger than the lateral moraines (Licciardi and others, 2014). Inset shaded-relief gray area is light detection and ranging (lidar) image along the Teton fault.

Figure 16. Dated boulder on the Taggart Lake moraine with an exposure age of 15.2 ± 0.3 ^{10}Be thousand years ago. Avriel Schweinsberg stands for scale on right side of boulder. The dated sample is from the top of the boulder and is well above where fire spalling is not likely to be a problem in determining age.

Stewart Draw

The Stewart Draw moraines are on the lower slope of the Teton Range 5 km south of Taggart Lake. The Teton fault crosses the upper reaches of this hummocky moraine complex with apparent left lateral offset of 11–13 m (K.L. Pierce, field locality 93P20).

Phelps Lake Moraines

The Phelps Lake moraines extend ~3 km out onto the floor of Jackson Hole and have high lateral moraines that flank a deep 2.4-km-long lake. Two boulders on the left lateral moraines average 19.4 ± 1.7 ka, whereas three boulders on the end moraines average 16.1 ± 0.2 ka. The considerably younger age for the end moraines may result from progressive glacial scouring and deepening of the Phelps Lake basin, which would have left the older high lateral moraines perched above the Pinedale glacier surface that later deposited the end moraines.

Granite Canyon Moraines

Moraines at the mouth of Granite Canyon form a nearly circular arc of multiple closely nested ridges that extends out about 2 km onto the floor of Jackson Hole (fig. 15). Seven boulders were sampled, but only one has yet been analyzed, yielding an age of 16.7 ± 0.3 ka.

Valley Glaciers on the East Side of Jackson Hole

The entire mountain valley of Flat Creek contained a Pinedale glacier about 20 km long (fig. 4). This glacier deposited moraines at the valley mouth on the east side of Jackson Hole and built a large glacial-outwash fan (fig. 12). South of Flat Creek, the Sheep Creek glacier (fig. 4, see also fig. 12) headed on the north side of Jackson Peak and extended about 10 km. In its terminal area, the Pinedale Sheep Creek glacier deposited moraines that are perpendicular to the ice-marginal channels and morainal ridges of the Bull Lake glaciation (fig. 12).

Valley Glaciers in the Gros Ventre Drainage

Extensive mountain valley glaciers formed in the Gros Ventre Range and deposited moraines that extend down the main drainages locally to the Gros Ventre River (fig. 4). Lagas (1984) considered the outer part of these moraines to be Bull Lake following the classic Rocky Mountain model of Bull Lake moraines occurring just outside of Pinedale moraines. But the outer moraines have equally fresh morphology, including undrained depressions, and we conclude that they are all of Pinedale age.

Greater Yellowstone Glacial System in Jackson Hole

Although local valley glaciers helped create the spectacular landscapes of the Teton Range, the glacial features in Jackson Hole stem mostly from glaciers that invaded Jackson Hole from the east and north along the southern margin of the GYGS. The bulk of the glacial outwash flooring Jackson Hole and most of the moraines in central and northern Jackson Hole were deposited by glaciers emanating from the GYGS (fig. 1).

Glacial Lobes of Greater Yellowstone Glacial System in Jackson Hole and Their Change Through Time

Glacial lobes along the southern margin of the GYGS flowed down the valleys of Buffalo Fork, Pacific Creek, and Snake River (fig. 17). The glacial geologic history of Jackson Hole is complicated but enriched because the downvalley extent of these lobes changed through time (fig. 18). The southern part of the Teton Range produced separate valley glaciers that terminated commonly at the foot of the range, but the glaciers from the northern part of the Teton Range coalesced with the Snake River lobe of the GYGS in Pd-2 and Pd-3 time. These changes through time can be explained by the progressive building of the southern part of the GYGS source area southwestward through time towards the source of orographic snowfall, which is associated with storms moving eastward up the Snake River Plain and then rising up onto the Yellowstone Plateau and the YCHT (fig. 2).

Buffalo Fork Glacial Lobe

This lobe flowed into Jackson Hole from the east and headed on the west side of the high Absaroka Range that extends about 33 km north from Togwotee Pass (fig. 17). It culminated at a length of 55 km (35 miles) from the ice divide of the Pd-1 advance but had retreated at least 20 km by Pd-2 time.

Pacific Creek Glacial Lobe

This lobe headed in the Two Ocean Plateau area, reached a length of more than 60 km, and flowed into Jackson Hole from the northeast (fig. 17). The Pacific Creek lobe was extensive in all three phases of the Pinedale glaciation.

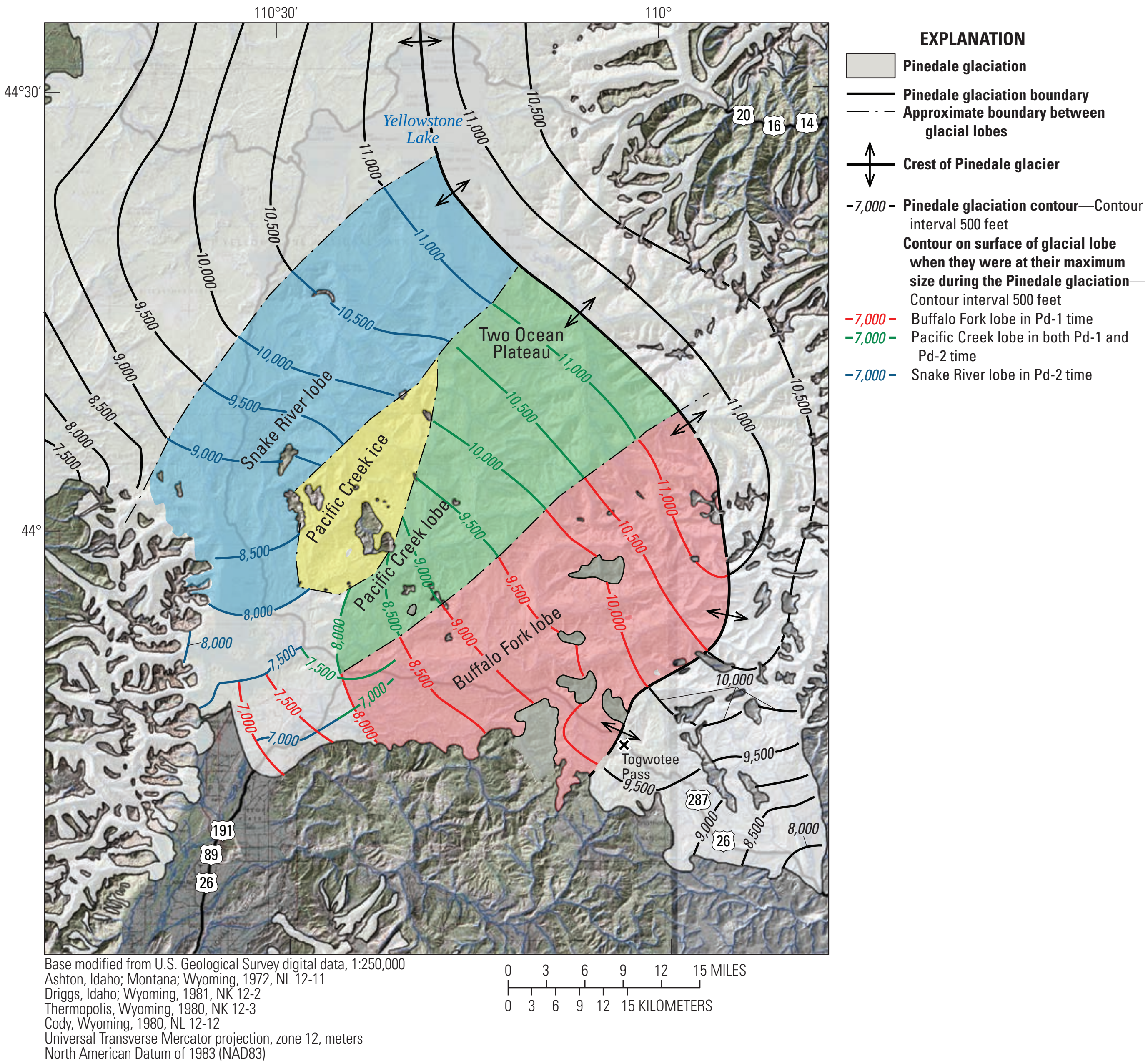


Figure 17. Three glacial lobes at their maximum that fed into Jackson Hole along the southern margin of the Greater Yellowstone Glacial System. The lobes are: (1) Buffalo Fork lobe that headed in the high Absaroka Range; (2) the Pacific Creek lobe that headed on the Two Ocean Plateau and beyond; and (3) the Snake River lobe that headed on the Yellowstone Plateau above the Yellowstone Lake. Green contours are not shown near terminus. The Buffalo Fork lobe culminated earliest and before the Snake River lobe extended into Jackson Hole, whereas the Snake River lobe culminated latest at a time when the Buffalo Fork lobe had receded at least 20 kilometers (12 miles). The yellow area designates glacial flow that terminated in the Pilgrim Creek drainage and deposited an extensive gravelly fill there.

GLACIAL PHASE	GLACIAL LOBE		
	Buffalo Fork lobe (easternmost)	Pacific Creek lobe	Snake River lobe (westernmost)
Pd-1 (oldest)	Equal	Equal	Smallest (not confluent)
Pd-2	Smallest (not confluent)	Equal	Equal
Pd-3 (youngest)	Smallest (not confluent)	Equal	Equal

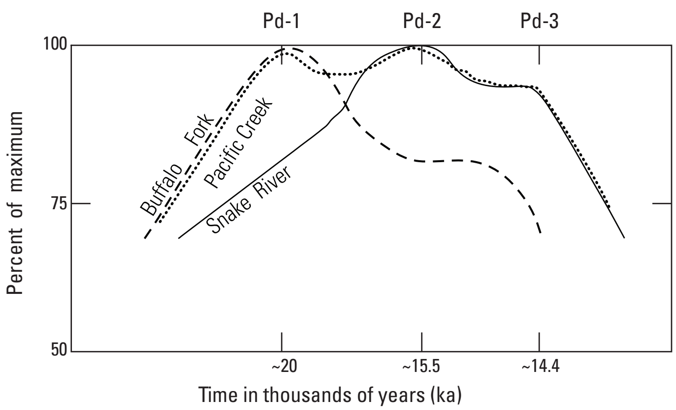


Figure 18. Relation between the distal ends of the three glacial lobes feeding into Jackson Hole through time. Lobes of ice feeding into Jackson Hole were channeled by the valleys of the Buffalo Fork from the east, Pacific Creek from the northeast, and the Snake River from the north. The upper part of this figure shows that the relative dominance (southerly extent) of these lobes changed through time. This pattern reflects glacial buildup and advance first from the high Absaroka Range followed later by buildup on the Yellowstone Plateau. For the Greater Yellowstone Glacial System, age relations indicate glacial buildup migrated westerly towards the source of orographic snowfall of storms carrying moisture up the lowland of the eastern Snake River Plain. As this southwesterly buildup progressed, the glaciers east of this buildup became in a precipitation (snow) shadow and they receded.

Snake River Glacial Lobe

The ice source region for this lobe was on the Yellowstone Plateau on an ice divide above Yellowstone Lake. The lobe was more than 70 km long and flowed into Jackson Hole from the north (figs. 9 and 17). In Pd-1 time, the Snake River lobe did not join the other lobes and was more than 24 km shorter than during its greatest Pinedale advance. The height and extent of this Snake River lobe reflect the building of an extensive ice cap on the Yellowstone Plateau in Pd-2 and Pd-3 time.

Pilgrim Creek Drainage

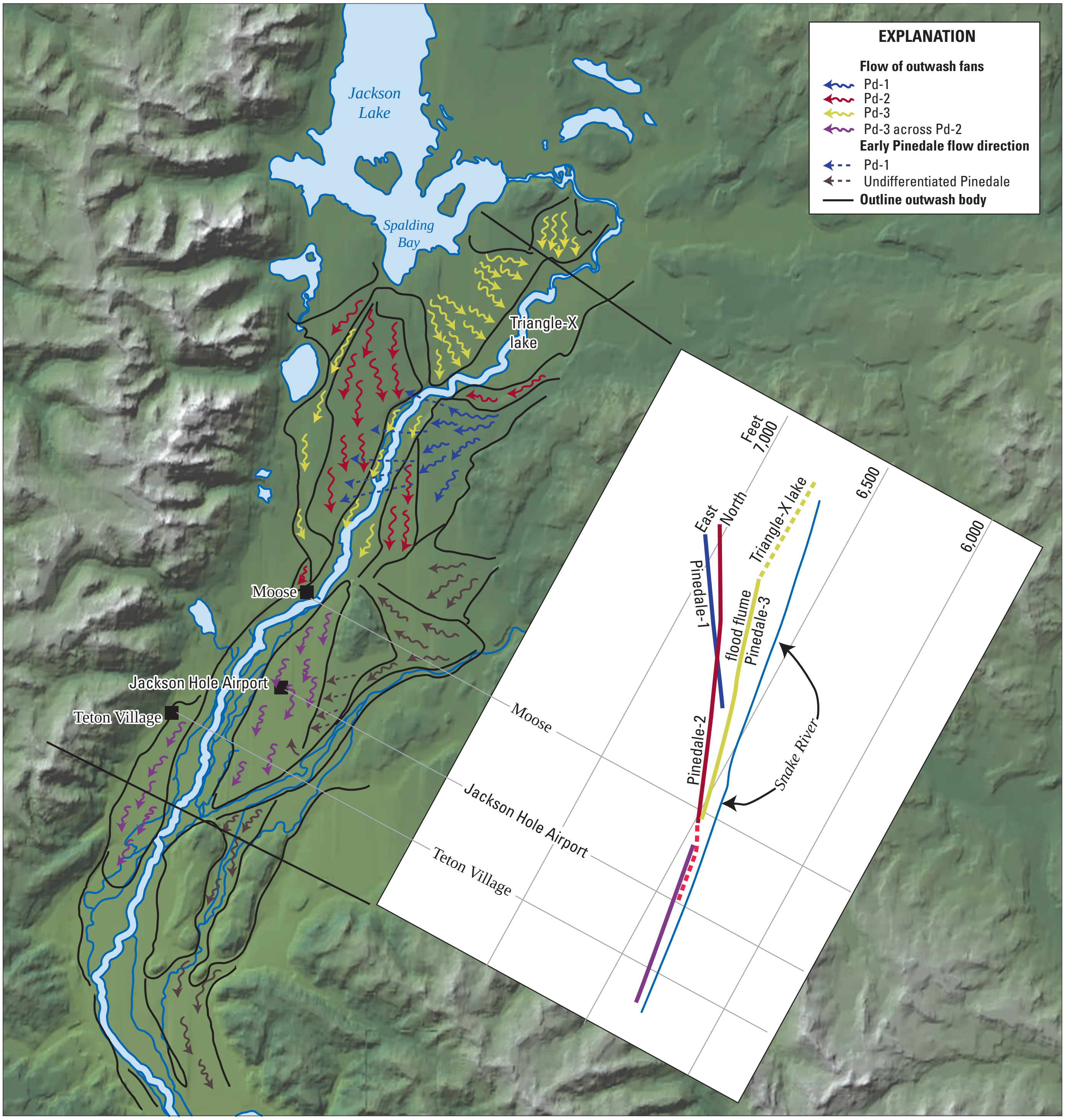
Glacial flow also overtopped the divides and terminated in the Pilgrim Creek drainage (fig. 17, yellow area). The Snake River lobe blocked the lower end of the drainage and a large amount of gravelly sediment was deposited in that drainage. Post-glacial erosion of this unconsolidated gravelly fill results in the continued active building of the large Pilgrim Creek alluvial fan.

Outwash-Dominated Glacial Deposits in Jackson Hole

The volume and prominence of glacial outwash from the GYGS is a key and unusual feature of the glaciation of Jackson Hole (figs. 19 and 20). Commonly in mountain glaciation, end moraines stand well above the associated glacial outwash, in part because the outwash is only 10 m or less thick. However, the glacial deposits on the southern margin of the GYGS in Jackson Hole are dominated by outwash of cobble gravel up to 100 meters thick that is rich in recycled quartzite roundstones. Glacial moraines associated with the GYGS in this area are commonly nearly submerged by buildup of outwash on their distal (down flow) side. The source of the outwash is extensive, weakly indurated deposits of quartzite conglomerate mostly in the Late Cretaceous Harebell Formation and Paleocene Pinyon Conglomerate (Love and others, 1992; Love and Christiansen, 1985). The Pinedale glacial history is most readily appreciated and understood by the buildup of major outwash fans which reflect the changing relations between Pinedale-1, -2, and -3 aged glaciers.

Two factors are likely responsible for the great thickness of this outwash gravel: (1) the abundant supply of coarse gravel as discussed above; and (2) the downward flexing of the lithosphere by the large mass of the GYGS. Downward flexure near the margins of the GYGS would have lessened the gradient of the glacial Snake River, thereby encouraging the deposition and accretion of thick outwash sequences that acted to restore the original equilibrium drainage gradient (Anderson and others, 2014). A similar crustal depression and rebound was simulated by Hampel and others (2007) to model relatively high rates of offset on the Teton fault during deglaciation and crustal rebound. Downward flexing of the crust by the weight of the GYGS may also explain the thick outwash deposition (50 m) by the northern Yellowstone outlet glacier of the GYGS (Pierce, 1979; Pierce and others, 2014).

The buildup of outwash is also demonstrated by the “cast” of the glacier snout, which is preserved after ice withdrawal as an escarpment that rises steeply downvalley toward the head of outwash fans. The top of the cast is commonly 30–60 m high in the Jackson Hole area. Four prominent examples include: (1) the outwash-glacial ice boundary of the Pd-1c near the Snake River Overlook (fig. 4); (2) the change in level at the head of the Pd-2 Spalding Bay outwash fan 80 m above the adjacent floor of Jackson Lake (see ahead to figure 28 in section Type Area Pd-2 Glaciation); (3) the head of the Pd-3



NOT TO SCALE

VERTICAL SCALE GREATLY EXAGGERATED
DATUM IS SEA LEVEL

Figure 19. Pinedale outwash terraces in Jackson Hole showing their map and profile relations. The outwash relations show Pinedale glacial sequence more clearly than do the glacial moraines. The Airport terrace is interpreted to have experienced Pd-3 floods across an original Pd-2 terrace. Black wavy arrows indicate paleo-streamflow on Pinedale alluvial fans and black dashed arrows indicate paleo-streamflow on early Pinedale fan of Gros Ventre River. Figure by Carol Thickstun and Lawrence Ormsby.

Figure 20. Oblique aerial photograph looking south down the Snake River and showing three ages of Pinedale outwash terraces. On the upper left is Antelope Flats formed by the Pd-1 terrace that heads in eastern Jackson Hole. On the right middle is Baseline Flat formed by the Pd-2 outwash fan that heads at Spalding Bay. The lower half of the picture is The Potholes terrace of Pd-3 age. Farther down the Snake River is the inset Pd-3 terrace that acted as the "flood flume" for floods that pulsed through the Triangle X-2 lake. Oblique color aerial photograph by Michael Collier of Flagstaff, Arizona.

Potholes channelway outwash fan 40 m above the adjacent floor of Jackson Lake; and (4) the head of the South Landing channelway 55 m above the adjacent floor of Jackson Lake.

Pinedale-1, -2, and -3 Outwash Fans

Glacial outwash fans associated with the Pinedale GYGS form important and clearly recognizable topographic features in Jackson Hole. These deposits present the most readily identifiable landscape features that define the Pinedale glacial-geologic sequence related to the GYGS in Jackson Hole (figs. 19 and 20). Moraines of the GYGS are also present, but these represent comparatively minor features in this outwash-dominated system. For this reason, the Pinedale outwash fans are briefly described before the associated glacial moraines.

The Pd-1 outwash fan heads on the east side of central Jackson Hole and occupies most of Antelope Flats (fig. 19, blue wavy arrows; fig. 20). This fan forms a cone that subtends an arc of 90 degrees. Channel patterns on the northern part of this fan indicate flow from east to west and this outwash terrace projects westward to well below the Pd-2 outwash level to the west of the Snake River.

The Pd-2 fan heads just south of Spalding Bay (fig. 19, red wavy arrows). The head of this fan is 10 km northwest of the head of the Pd-1 outwash fan. The Pd-2 Spalding Bay fan is up to 5 km wide and more than 10 km long.

Two Pd-3 glacial outwash fans are clearly visible in the landscape. The Potholes outwash fan heads at the glacier front that filled Spalding Bay and the South Landing outwash fan heads at a glacier front that occupied South Landing. In Pd-3 time, the Snake River lobe had retreated to a position just outside the present margin of Jackson Lake. These two fans were built into space that had been occupied by the Pd-2 advance and hence must be younger than the Pd-2 glacial position.

Pinedale-1 Glaciation

Type Area

The type Pd-1 moraine is on the east side of Jackson Hole at the head of Antelope Flats (fig. 21). This phase had been called "Burned Ridge" (Love and others, 1992), but is here called Pd-1 for both simplicity and because the actual topographic feature named Burned Ridge consists of two ages of moraines here designated Pd-1 and Pd-2. Three distinct moraine positions are recognized as part of the Pd-1 phases (Pd-1a, 1b, 1c) and are described below.

The best-displayed Pd-1 moraine (Pd-1c) can be found a short distance east of the Snake River Overlook across U.S. Highway 27, and locally consists of as many as two moraine ridges separated by deep kettles (figs. 22 and 23). This Pd-1c ice margin is fronted with glacial outwash that rises to the northeast and becomes a kame terrace more than 100 m above the Snake River, with a steep escarpment on its north side that forms a collapsed cast of the Pd 1c glacier snout.

The Pd-1 moraine ridges are devoid of large boulders (greater than1 m), which makes them poorly suited for cosmogenic dating. Two small boulders on these moraines yielded an average age of 14.7 ± 0.2 ka, but these are regarded as erroneously younger than the true age of the Pd-1c moraines because of concerns about post-depositional exhumation, disturbance, and snow cover of the rather small boulders (Licciardi and Pierce, 2008). Furthermore, these two Pd-1c ages are younger than a large number of cosmogenic ages on Pd-2 features (see Pinedale-2 Glaciation) and therefore not consistent with stratigraphic relations. The Pd-1 advance down the Buffalo Fork is most likely similar in age to earlier Pinedale maxima found elsewhere in the Rocky Mountains (for example, Gosse and others, 1995; Pierce, 2004), and we speculate that the Pd-1 culmination may correspond with the age of the oldest recognized Pinedale moraines from the Teton Range, which are dated to ~21–18 ka from two boulders on the high left-lateral moraine flanking Phelps Lake (fig. 15) (Licciardi and others, 2014).

This Pd-1c moraine and associated outwash is the innermost of the three Pd-1 moraine positions. About 2 km farther down valley are the Pd-1b end moraines and associated kettles (fig. 22). These moraines have scattered trees and are nearly completely buried by outwash. The outermost Pd-1 ice position, Pd-1a, is 1 km farther down valley; it is represented only by the occurrence of multiple kettles presumably formed by detached ice blocks along the Pd-1a ice margin (fig. 22). These glacial positions (Pd-1b and Pd-1c) have associated outwash from the same source. Outwash channel patterns show that Pd-1a ice blocks were buried by Pd-1b outwash and that Pd-1b outwash is in turn overlapped by Pd-1c outwash. For the Pd-1c outwash, the braided-channel pattern indicates flow near the Snake River Overlook was from east to west.

East of the Type Area

From the Antelope Flats glacier margin (altitude 2,100 m; 6,900 ft), the southern margin of the Pd-1 glacier can be traced eastward as it climbs 600 m (2,000 ft) over 45 km to the Blackrock Meadows area (fig. 21; altitude 2,950 m, 9,000 ft). Glacial flow was to the southwest, and contours on the reconstructed ice surface trend SE to NW (fig. 21). Glacial flow was therefore oblique to the southern margin of the Pd-1 glacier. In greater detail, the Pd-1 ice limit eastward from Antelope Flats is defined by moraines and kame terraces on the lower slopes of the Mount Leidy highlands (fig. 21). For several kilometers along the steep slopes of the Mount Leidy highlands, the boundary is obliterated by landsliding. Spread Creek (fig. 21) now flows in an ice-marginal position a kilometer or so inside this Pd-1 limit. Farther east, the deposits along the southern margin of the Pd-1 glacier are well represented by thick inwash deposits dammed against this ice margin in the lower reaches of Skull Creek, South Fork Spread Creek, and North Fork Spread Creek (fig. 21). About 1.7 km south of Baldy Mountain, Lily Lake is a kettle lake formed by a Pd-1 ice block that was buried in a preexisting canyon of Spread Creek. The Pd-1 glacier also draped a moraine along the crest of Baldy Mountain at an altitude of 2,620 m (8,600 ft).

Blackrock Meadows (fig. 21) was occupied by a glacier at least 150 m (500 ft) thick in Pd-1 time as indicated by sharp-crested lateral moraines on the valley slope south of Blackrock Meadows. Along Forest Service Road 30-100 about 0.7 km (0.5 mile) from the junction with U.S. Highway 287, striated bedrock of the Absaroka Volcanic Supergroup combined with rat tails indicates glacial flow to N 85° W. This glacier flowed west out of the Blackrock Meadows area to join the Buffalo Fork glacial lobe.

The extensive glacial deposits on the high bench south of Buffalo Fork (fig. 21) were originally named the Buffalo glaciation by Blackwelder (1915) and considered to be pre-Bull Lake in age. The main reason for this pre-Bull Lake age assignment was that these glacial deposits are perched on a bench as much as 450 m (1,500 ft) above the Buffalo Fork, and Blackwelder inferred this amount of erosion had occurred since their deposition. Blackwelder identified this landscape as the Blackrock Cycle of stream erosion and interpreted the field relations to indicate an age sufficiently old enough to accomplish an inferred 450 m (1,500 ft) of post-depositional erosion. We agree with Richmond (1976) that these deposits are instead indicative of the great thickness of the Buffalo Fork glacial lobe rather than a reflection of post-depositional erosion. The moraines have fresh morphology, weak soils, numerous ponds, and little evidence of boulder weathering, all of which are consistent with a Pinedale age.

West and North of the Type Area

Across the Snake River from the Snake River Overlook is the landform named Burned Ridge (figs. 4 and 21). Burned Ridge is a glacially complex landform consisting of Pd-1 moraine that was eroded and then apparently draped in places

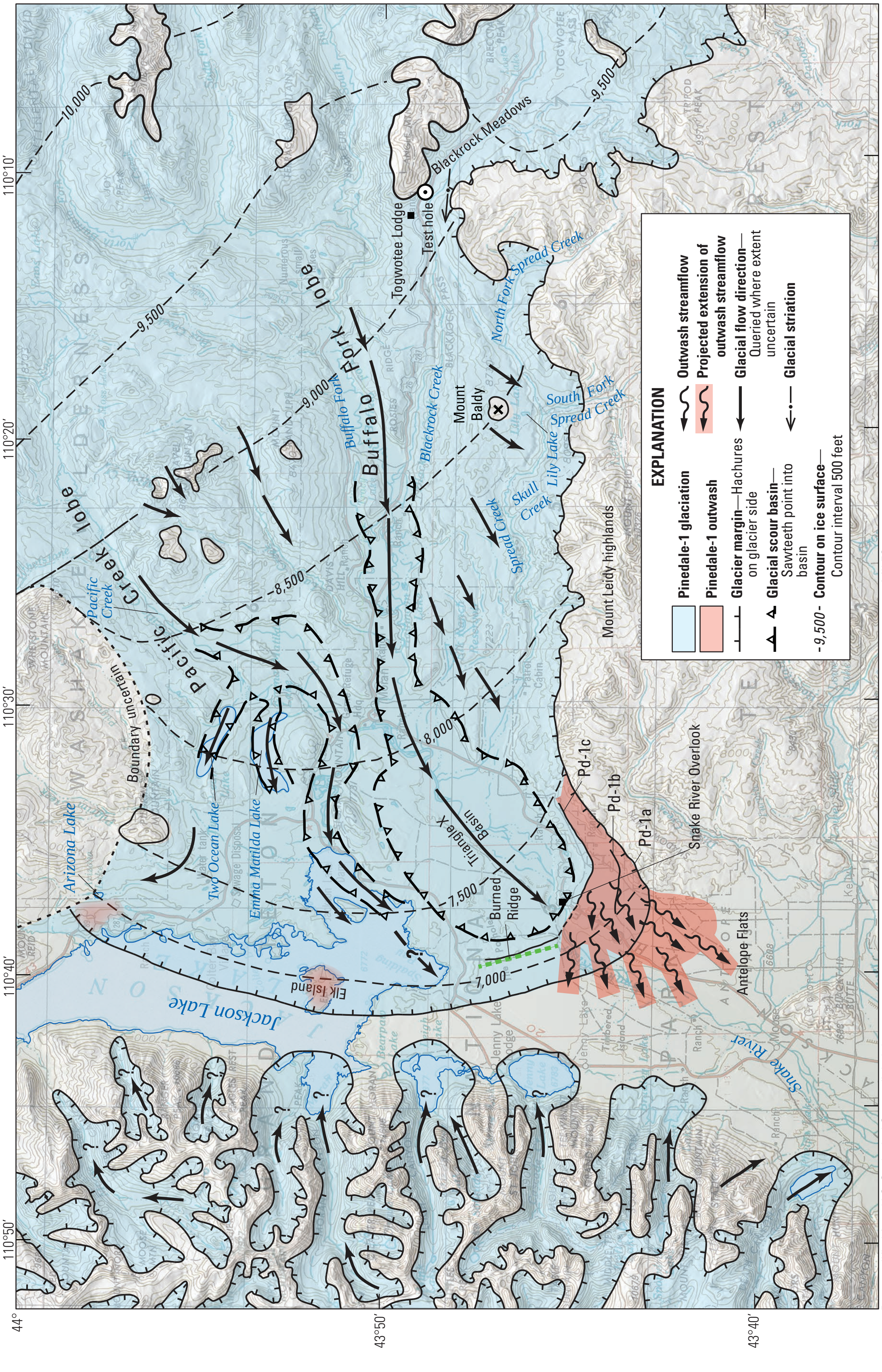


Figure 21. Pd-1 glaciation and associated glacial outwash of the southern Greater Yellowstone Glacial System. The Buffalo Fork lobe was most extensive at this time (Pd-1) but the Snake River lobe was many kilometers from its ultimate culmination. Meltwaters of the ice-marginal paleo-Spread Creek flowed along the southern margin of the Buffalo Fork glacial lobe and debouched onto the floor of Jackson Hole where they deposited thick outwash to form Antelope Flats. In the Antelope Flats area, the Pd-1 is divided into three glacial positions with associated outwash: Pd-1a (kettles only); Pd-1b outwash in front of nearly buried moraines; and Pd-1c outwash in front of well-defined moraines that are partly buried by glacial outwash. On the north side of the Pd-1c moraine is a steep slope 60 meters (200 feet) high inherited from the original ice-contact slope where the glacier snout once stood. Figure by Carole Thickstun and Lawrence Ormsby.

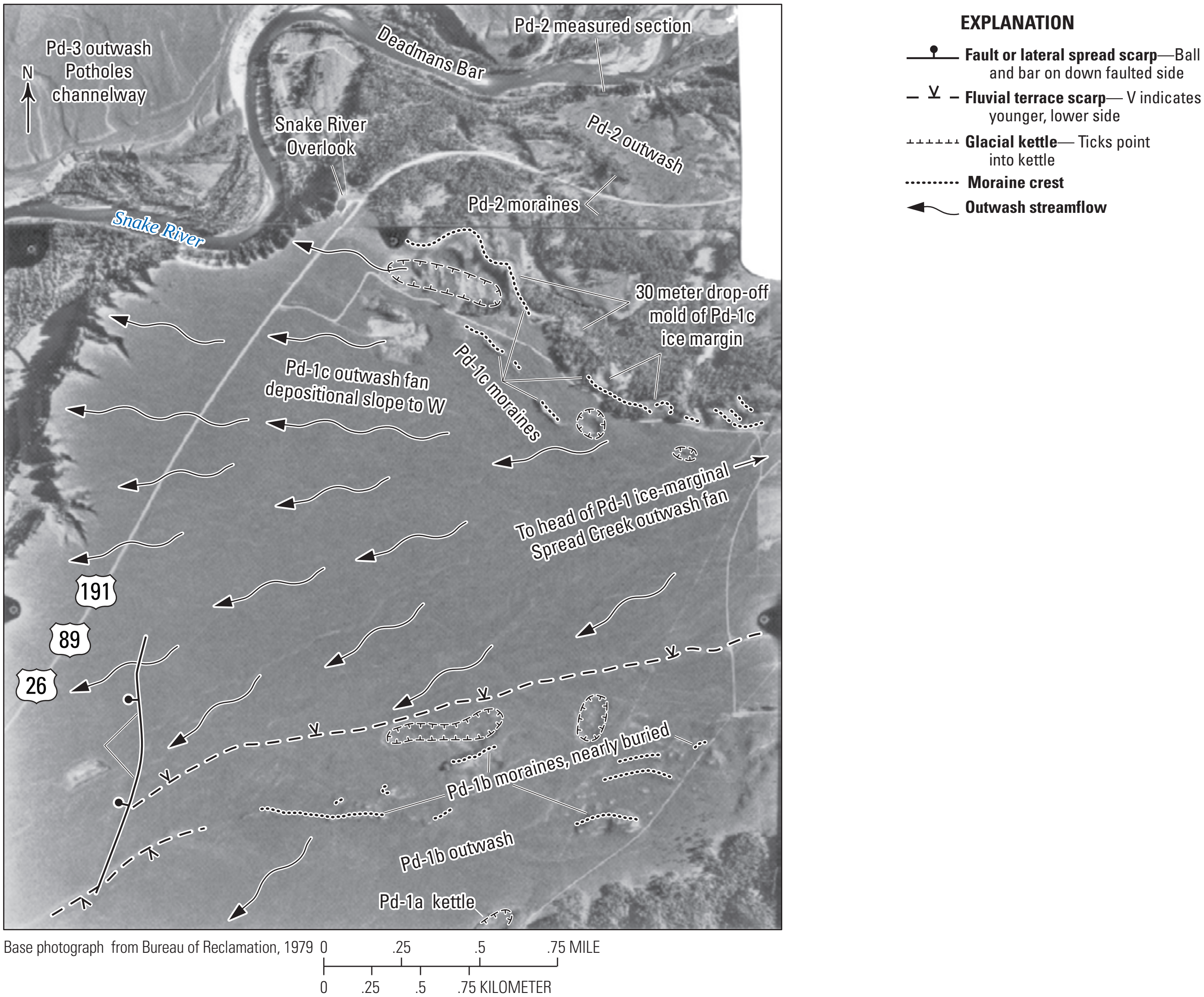


Figure 22. Low sun-angle aerial photograph showing Pd-1c and Pd-1b moraines and associated outwash. The ice-marginal Spread Creek built an outwash fan with an arc of 45° that slopes to the west and southwest. Moraines of Pd-1c and Pd-1b age are largely buried by more than 60 meters of quartzite-rich outwash supplied by the ice-marginal paleo-Spread Creek. A deep kettle is shown between two Pd-1c moraines. A degraded mold of Pd-1c glacier snout as high as 60 meters occurs just north of the Pd-1c moraines. Note the subdued channel pattern of the Pd-1 outwash compared to the Pd-2 outwash shown in figures 29 and 31. In the upper right of the photograph are the Pd-2 moraines and outwash of the Hedrick Pond bench as well as the location of the Pd-2 measured section shown in figure 30.

Figure 23. Pd-1c moraine at north end of Antelope Flats. The moraine consists mostly of quartzite cobbles and also contains clasts of Absaroka volcanic andesite and Tensleep Sandstone. On the middle left is a deep kettle and beyond that is a flat terrace surface on which the Snake River Overlook is located.

with Pd-2 moraines. Shallow kettles on Baseline Flat just west of the Snake River and 2 km southwest of Burned Ridge probably represent Pd-1a or Pd-1b ice blocks buried by Pd-2 outwash. Farther north, Pd-1 deposits may compose most of the sediment mass forming the west side of Spalding Bay. Gravels exposed in the bluffs of Elk Island are most likely Pd-1 outwash deposited to the west of (beyond) the Pd-1 glacier (fig. 21). This outwash remnant pre-dates the glacial excavation of Jackson Lake and was subject to subglacial scour in Pd-2 and Pd-3 time.

As shown in figure 21, west-flowing Pd-1 ice scoured out the troughs of Two Ocean Lake and Emma Matilda Lake and the deep trough that underlies the Jackson Lake Dam. From this area north to the Arizona Lake area (fig. 21), Pinyon-type quartzite cobbles are common in the glacial deposits. Formations rich in quartzite cobbles are well represented on the northwest side of the Teton Range, (Love and others, 1978, 1992), but there is little or no bedrock source of quartzite cobbles in the source terrain of the Snake River lobe. In the Arizona Creek drainage (fig. 21, the first drainage north of Arizona Lake), the Late Cretaceous Bacon Ridge Sandstone has only a quartzite pebble zone near its base (Love, 1974). No Pinyon-type quartzite is found in the Lizard Creek drainage, the next drainage to the north. From the Arizona Lake area (fig. 21) west to highway road cuts, as much as 20 m of glacial gravel rich in Pinyon-type quartzite cobbles and poor in rhyolite is overlain by thin till richer in rhyolite and poorer in Pinyon-type quartzite. A likely source for these Pinyon-type quartzite cobbles is from Pd-1 glacial flow of the combined Pacific Creek and Buffalo Fork lobes that both scoured out the basins of Two Ocean and Emma Matilda Lakes and advanced up the Snake River valley (fig. 21). The rhyolite-rich till mantling this gravel was deposited by the south-flowing Snake River lobe in Pd-2 and Pd-3 time.

Triangle X-1 Lake

In Pd-1 time, the Buffalo Fork lobe excavated an inferred deep basin upstream from the Snake River Overlook. Upon recession of Pd-1 ice, the Triangle-X basin (fig. 21) probably contained a proglacial lake, here called the Triangle X-1 lake, although such sediments are generally in the subsurface and not exposed. Near the confluence of the Buffalo Fork and Snake River drainages, lacustrine deposits of possible Triangle X-1 age extend to as much as 30 m below the surface (McGreevy and Gordon, 1964). Seven kilometers to the south, a water well at the Moose Head Ranch encountered

10 m (30 ft) of fine sediment which is either Triangle X-1 and (or) Triangle X-2 lake sediments. The abundant mud in the Pd-2 glacial till described in the section on the Hedrick Pond Bench probably represents the glacial plowing of this inferred paleo-lake.

Pinedale-2 Glaciation

During the Pd-2 glaciation, the Snake River lobe advanced into Jackson Hole and deposited the large Spalding Bay outwash fan (fig. 24). In Pd-2 as well as Pd-3 time, the Snake River lobe also excavated the Jackson Lake basin. The Snake River lobe and Pacific Creek lobe were confluent in Pd-2 time, but the Buffalo Fork lobe had receded upvalley from its former confluence with the Pacific Creek lobe (fig. 24). Subglacial sliding of the Snake River lobe also scoured and streamlined the landscapes on the east side of Jackson Lake, as shown later in figure 39.

The inner and outer Jenny Lake moraines can be correlated with Pd-2 and Pd-3 outwash of the GYGS (figs. 25 and 26). The relations at the land surface are shown in figure 25 but the moraine and outwash relations beneath the surface are likely different. The inner and outer Jenny Lake moraines enclose the 73 m (240 ft) deep Jenny Lake (fig. 25). A well site we selected and logged 0.9 km east of the Jenny Lake Lodge (fig. 25) penetrated 111 m (365 ft) of inferred Pinedale outwash gravel and bottomed in silt. The buildup of glacial outwash possibly thicker than 100 meters may help explain the egg-shape of Jenny Lake moraines, which are elongate perpendicular to rather than parallel to the orientation of the valley (Cascade Canyon) that contained the source glacier. J. David Love considered this anomalous shape to be important.

Type Area Pd-2 Glaciation

The large Pd-2 outwash fan extends south of Spalding Bay (figs. 24 and 26). The outwash fan heads at an altitude of 2,140 m (7,020 ft) and is preserved on both sides of the incised Spalding Bay channelway. The Mountain View Turnout is on this Pd-2a outwash (~0.1 km northeast of fig. 25). The Pd-2a, b, and c subdivisions are local distinctions in this area. On the west side and fronting the head of outwash at an altitude of 2,143 m (7,030 ft) is the type Pd-2 moraine. This moraine was deposited by the Snake River lobe that was joined along its west side by the Moran Canyon valley glacier as well as other valley glaciers from the northern Teton Range carrying Proterozoic boulders amenable for ^{10}Be dating. Although limited in area, the type Pd-2 moraine is characterized by very large boulders (fig. 27) that yield a cosmogenic age of 15.5 ± 0.5 ka (n = 5). The ^{10}Be ages combined with outwash and moraine stratigraphic relations in this area are critical to understanding the glacial history and interactions between the GYGS and the Teton Range (figs. 25 and 26).

On its west side, the large Pd-2 outwash fan buries northern and southern portions of the outer Jenny Lake moraine; thus, the Pd-2a and Pd-2b outwash and associated moraine must be younger than the outer Jenny Lake moraine. Boulders on the unburied eastern segment of the outer Jenny Lake moraine yield a mean exposure age of 15.2 ± 0.7 ka, although this is well within the error limits of the 15.5 ± 0.5 ka age for the demonstrably younger Pd-2a moraine (fig. 28). Both of these ages support a young age (~15.5 ka) for the culmination of the GYGS on its southern margin in Jackson Hole.

This Pd-2a Spalding Bay fan was incised in Pd-2b, Pd-2 c, Pd-3a and Pd-3b time (figs. 25 and 28), leaving terraces with scarps that are either shaded or highlighted in the photograph of figure 26. The lower two terraces (Pd-3a, Pd-3b) are graded to the Pd-3 moraines and grade downstream to a channel that flows around the outer margin of the inner Jenny Lake moraines (figs. 25 and 28). Boulders on the inner Jenny Lake moraines have an age of 14.4 ± 0.8 ka. The inner Jenny Lake moraines are contemporaneous with the lower two outwash levels (Pd-3a, Pd-3b) because the Pd-3 outwash stream would have spilled into the Jenny Lake basin if it had not been filled by a glacier.

In summary, the moraine-outwash sequence and ^{10}Be ages are as follows:

1. Outer Jenny Lake moraines, 15.2 ± 0.7 ka;
2. Pd-2a moraines, 15.5 ± 0.5 ka and Pd-2 outwash (Pd-2c) partly buries outer Jenny Lake moraines;
3. Pd-3a outwash (inferred to head at Pd-3 moraines); and
4. Inner Jenny Lake moraines, 14.4 ± 0.8 ka and Pd-3b outwash and channel in trench.

From the fan head at an altitude of 2,140 m (7,020 ft), the fan surface slopes south across Baseline Flat to an altitude of 2,020 m (6,630 ft) for 12 km to the Cottonwood Creek area. The slope near the fan head is 10 m/km (fig. 28). Over a distance of 4 km, the east side of this fan descends 60 m (190 ft) down to an altitude of 2,085 m (6,840 ft) where it intersected the Pd-1 outwash fan near the Snake River Overlook (fig. 4).

West of the Type Area

To the northwest from the type Pd-2a moraine (altitude 2,143 m; 7,030 ft) is an outwash surface ~10 m (30 ft) lower and of either Pd-2 or Pd-3 age. The ice front had receded about 0.25 km to the northwest and outwash was deposited at this lower level that includes the Cathedral Group Turnout (fig. 25). The outwash in the Cathedral Group Overlook area is also rich in quartzite cobbles from the Spalding Bay ice margin, whereas the moraine bordering this outwash is studded with large Proterozoic rocks from the Teton Range. In at least three places along the northern margin of this outwash, a drop off (ice cast) to the north requires the presence of a glacier at the time of outwash deposition.

The slope of the outwash from the Cathedral Group Scenic Turnout to String Lake is to the southwest at 10 m/km (65 ft/mi) (fig. 25). Some have interpreted the slope of this deposit to indicate 30 m (95 ft) of tilting adjacent to the Teton fault (Smith and others, 1990). Two observations indicate that

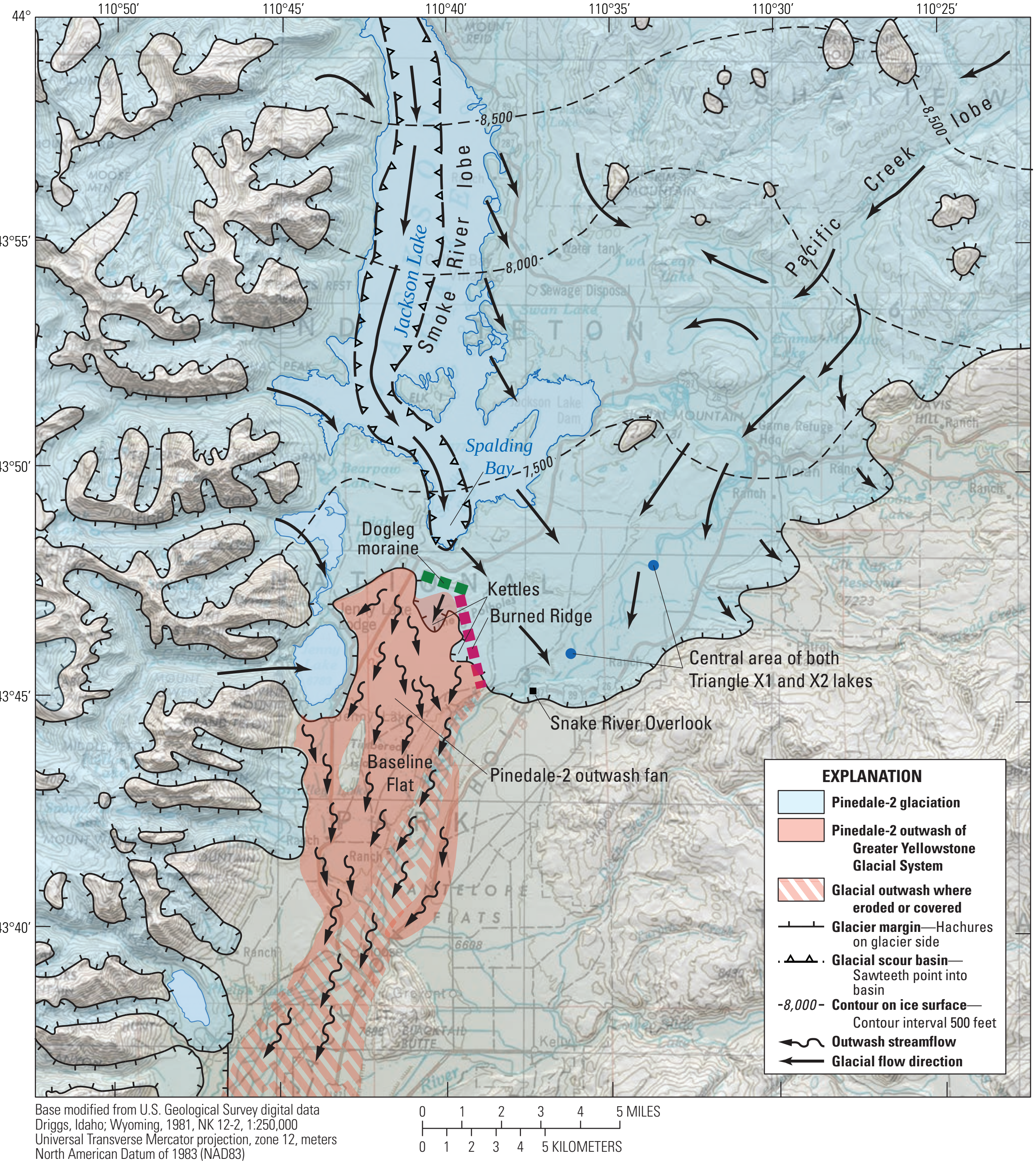


Figure 24. Pinedale-2 glaciation and associated outwash on the southern margin of the southern Greater Yellowstone Glacial System. The Pd-2 Snake River lobe excavated much of Jackson Lake and deposited a huge outwash fan that includes Baseline Flat. At this time, the Snake River and Pacific Creek lobes were confluent in the end moraine area, but the Buffalo Fork lobe had receded well upvalley permitting eastward advance of Pd-2 ice into areas previously occupied by the Buffalo Fork lobe.

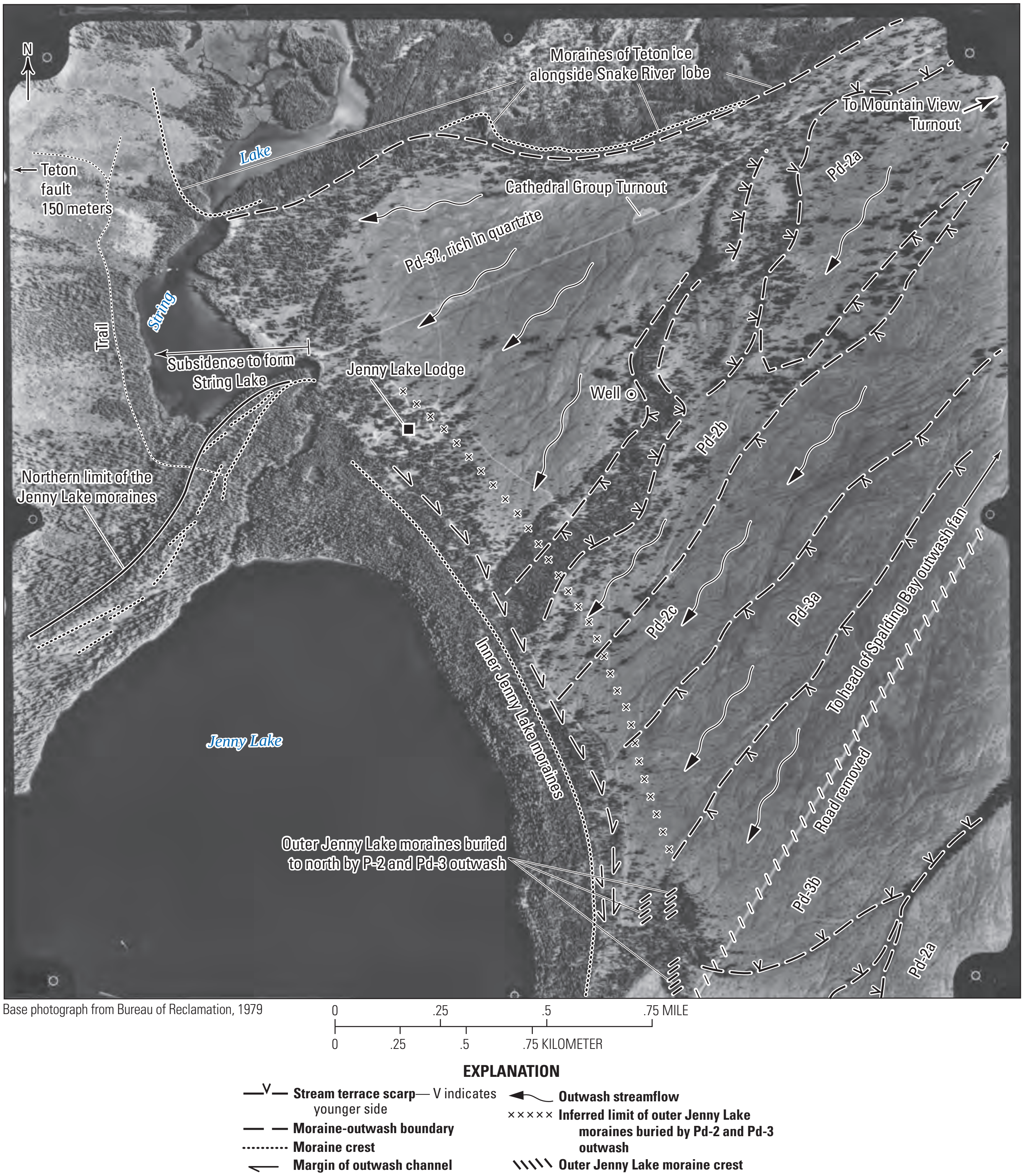


Figure 25. West part of the Spalding Bay outwash fan of the Greater Yellowstone Glacial System and the Jenny Lake moraines. The type Pd-2a moraine is at the head of the Pd-2a outwash 1 kilometer northeast of the upper right corner of the photograph. In north-center of photograph, the Cathedral Group outwash fan is rich in quartzite but fronts timbered moraines with huge boulders deposited by the combined Snake River-Teton Range lobe. The fines in the glacial moraines retain soil moisture and thus are forested, whereas soil water drains through the glacial outwash resulting in meadow vegetation. We selected and logged the well site near the center of the figure that produced large amounts of water from outwash.

Figure 26. Looking south down the Spalding Bay channelway. The type Pd-2a moraine is in the forest at the head of the outwash. During incision of the Pd-2a outwash fan, the strath terraces were cut. The eastern and largest part of the Spalding Bay outwash fan is to the left of the photograph. Only a short section of the outer Jenny Lake moraine is not buried by Pd-2 outwash and is shown by two "x's" labeled JL-o. The morning sun lights the scarps between the terraces that face east; whereas the main high west-facing scarp is in shadow. The inner Jenny Lake moraines (JL-i) are forested. Timbered Island is a remnant of Bull Lake moraine and outwash that is perched above the Pinedale outwash. Oblique color aerial photograph by Michael Collier of Flagstaff, Arizona.

Figure 27. Boulder sampled for Beryllium-10 dating in the type area of the Pd-2 moraine. The upper surface of this large boulder that Jennifer Pierce is pointing to was sampled. Field examination concluded this approximated the original glaciated surface. Teton Range glaciers were carried alongside the Snake River lobe of the Greater Yellowstone Glacial System and thus provided large granitic boulders suitable for cosmogenic dating.

most of this slope is depositional rather than tectonic. First, at the time of deposition, contours would be perpendicular to the braided-channel pattern. Thus for deposits of streams that flowed southward parallel to the fault, subsequent tilting into the fault would rotate contours clockwise. Second, the braided-channel pattern is so close to perpendicular to the contours that we cannot discern any rotation by this criterion. The post-glacial tectonic tilting is only a small fraction of the original depositional slope of the outwash gravel deposits. The original depositional slope of the Pd-2a fan where its slope parallels the Teton fault is about 13.2 m/km (70 ft/mi). Post-glacial downdropping of 15 m (50 ft) on the 16-km wide hanging wall of the Teton fault in this vicinity would produce a tilt of 0.9 m/km (5 ft/mi). This estimate of the tectonic tilt (0.9 m/km) added to the depositional slope of 13 m/km is an increase of only ~7 percent which is probably too small to be distinguished.

The Pd-2 margin of the Snake River lobe crosses String Lake (near the picnic area), and is represented by large residual boulders in String Lake. The Pd-2 margin of confluent GYGS and Teton glaciers (Paintbrush, Leigh, and Moran Canyons) rises from String Lake to the northwest along the Teton front to where it crosses the Paintbrush trail at an altitude of ~2,210 m (7,250 ft).

Dogleg Moraine

The term “dogleg” is applied to this moraine because it trends west at a high angle and projects from the north end of the glacial feature known as Burned Ridge (fig. 24). This Dogleg “moraine” does not have the form of a typical Pinedale moraine. In contrast to most moraines of the last glaciation in mountainous terrain, it has a broad and not especially bouldery crest. The ice-proximal side slopes rather smoothly to the north. The outwash on the south side is so thick that little of the moraine stands above the outwash. One hypothesis is that the Dogleg moraine is outwash gravel and other sediment that was thrust southward by Pd-2 ice advancing out of the Spalding Bay area. This may be similar to glaciotectonic moraine processes at Cape Cod, Massachusetts (Oldale and O’Hara, 1984), and in Iceland (Benediktsson and others, 2010).

Burned Ridge Area

From the east end of the Dogleg moraine south to the Burned Ridge area (fig. 24), glacial geologic relations are complex. Along the eastern margin of the large Pd-2 Spalding Bay fan, incised channels assigned a Pd-2b age are located as follows: (1) a long channel incised 3–6 m (10–20 ft) that heads at an altitude of about 2,135 m (7,000 ft) in the right angle between Burned Ridge and the Dogleg moraine (figs. 24 and 29); and (2) a short channel that heads at an altitude of 2,105 m (6,910 ft) near the south end of Burned Ridge (fig. 29). For the east side of Burned Ridge, these channels require glacial streams to be at the altitudes of the channel heads alongside the Pd-2 glacier.

Two areas of kettles occur in Pd-2 outwash west of Burned Ridge. First, kettles as deep as 30 m (100 ft) occur in the right angle formed by the intersection of Burned Ridge and the Pd-2 Dogleg moraine (arrow in upper right end of outwash in figure 24). These kettles are at the head of the long, shallow Pd-2b channel eroded into the Pd-2a Spalding Bay outwash fan. The deep kettles indicate a terrain more than 30 m (100 ft) lower than present into which the Pd-2 ice advanced and left ice blocks that were then buried by Pd-2 outwash. Second, kettles on the southwest side of Burned Ridge 2.5 to 3.5 km northwest of the Snake River Overlook define a semicircle of buried ice blocks (fig. 29). On the north side of this lobe are three morainal ridges in the forested Burned Ridge landform that slope down to the west (fig. 29). These three morainal ridges were deposited by the same glacier that formed the kettles. This glacial advance through the Burned Ridge landform is inferred to have followed a valley eroded through the Pd-1c moraine. This paleo-valley may have been formed by the drainage from the lake in the Triangle X basin (fig. 21).

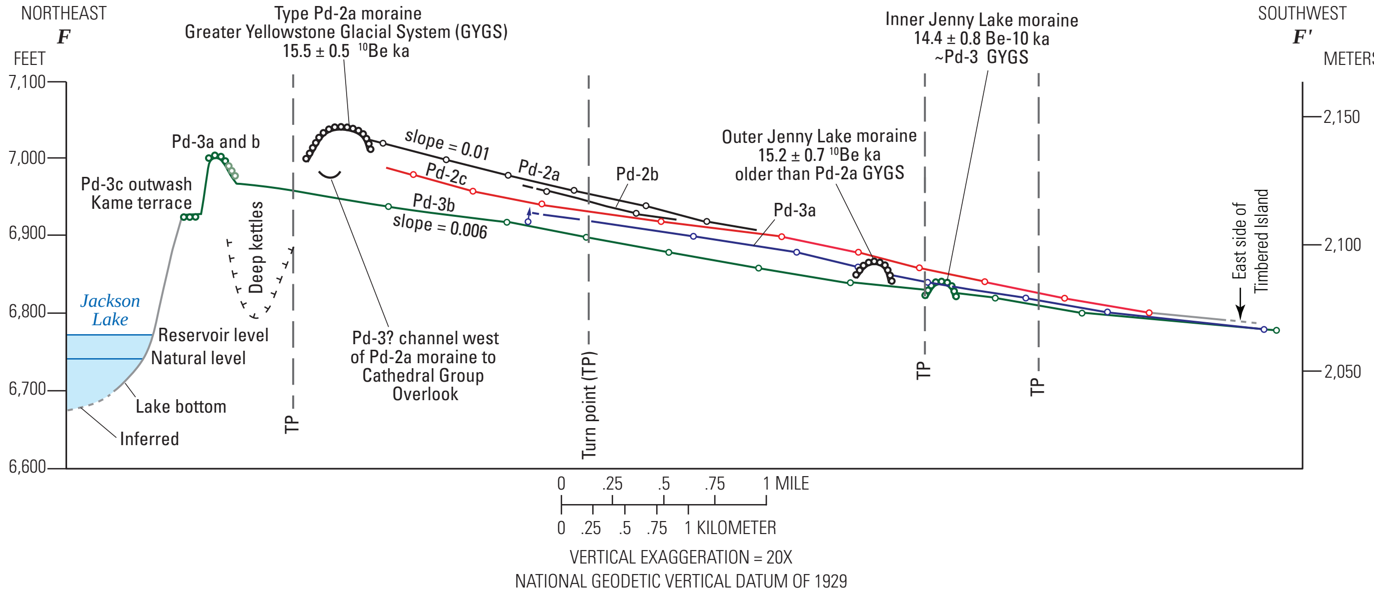


Figure 28. Terrace profiles projected to line *F–F'* (fig. 4) showing outwash relations between Pd-2 and Pd-3 moraines of the GYGS and the Jenny Lake moraines of glaciers from the Teton Range. The Pd-2a moraines of the GYGS included large boulders from the Teton Range amenable to cosmogenic dating and yielded an age of 15.5 ± 0.5 thousand years ago (ka). The Pd-2a outwash issuing from these moraines of the GYGS locally buries outer Jenny Lake moraines with an age of 15.2 ± 0.7 ka. This stratigraphic relation makes the Pd-2a moraines of the GYGS a little younger than the outer Jenny Lake moraines. Both ages support a remarkably young age of ~15.5 ka for the culmination of the GYGS on its southern margin. The inner Jenny Lake moraines have an age of 14.4 ± 0.8 ka and are of Pd-3 age, for the Pd-3 outwash would have spilled into Jenny Lake had not a glacier filled the lake basin at this time.

Hedrick Pond Bench

In earlier work (Pierce and Good, 1992), the Hedrick Pond phase of the Pinedale glaciation was named for Hedrick Pond that occurs on an outwash and moraine bench northeast of, and inset below, the Snake River Overlook (fig. 4). This is now considered to be a secondary type area for the Pd-2 advance that consists of an outwash terrace and associated moraines that form a bench 50 m (170 ft) above the Snake River and 45 m (150 ft) below the Pd-1 outwash terrace and moraines. The Snake River undercuts this bench and exposes the stratigraphic section diagrammed in figure 30 (location shown on fig. 22). Figure 30 shows about 25 m (80 ft) of fines-rich, stone-poor till capped by 15 m (48 ft) of gravel with lenses of flow till and sand. Such fines-rich glacial till is unusual in mountain glaciation, and here is inferred to result from the Pd-2 glacier advancing across Triangle X-1 lake sediments (fig. 24). The Pd-2 advance across the Triangle-X-1 lake sediments may also have been a glacial surge facilitated by unconsolidated wet lake sediments.

Pd-1 outwash gravels in the Snake River Overlook area slope to the west, and the Triangle X-1 basin probably drained farther to the west than the present outlet in this area. Thus, when the Snake River lobe advanced across the Triangle X-1 lake sediments in Pd-2 time, it probably also dammed drainages so the southeastward advance was across standing water on lake sediments.

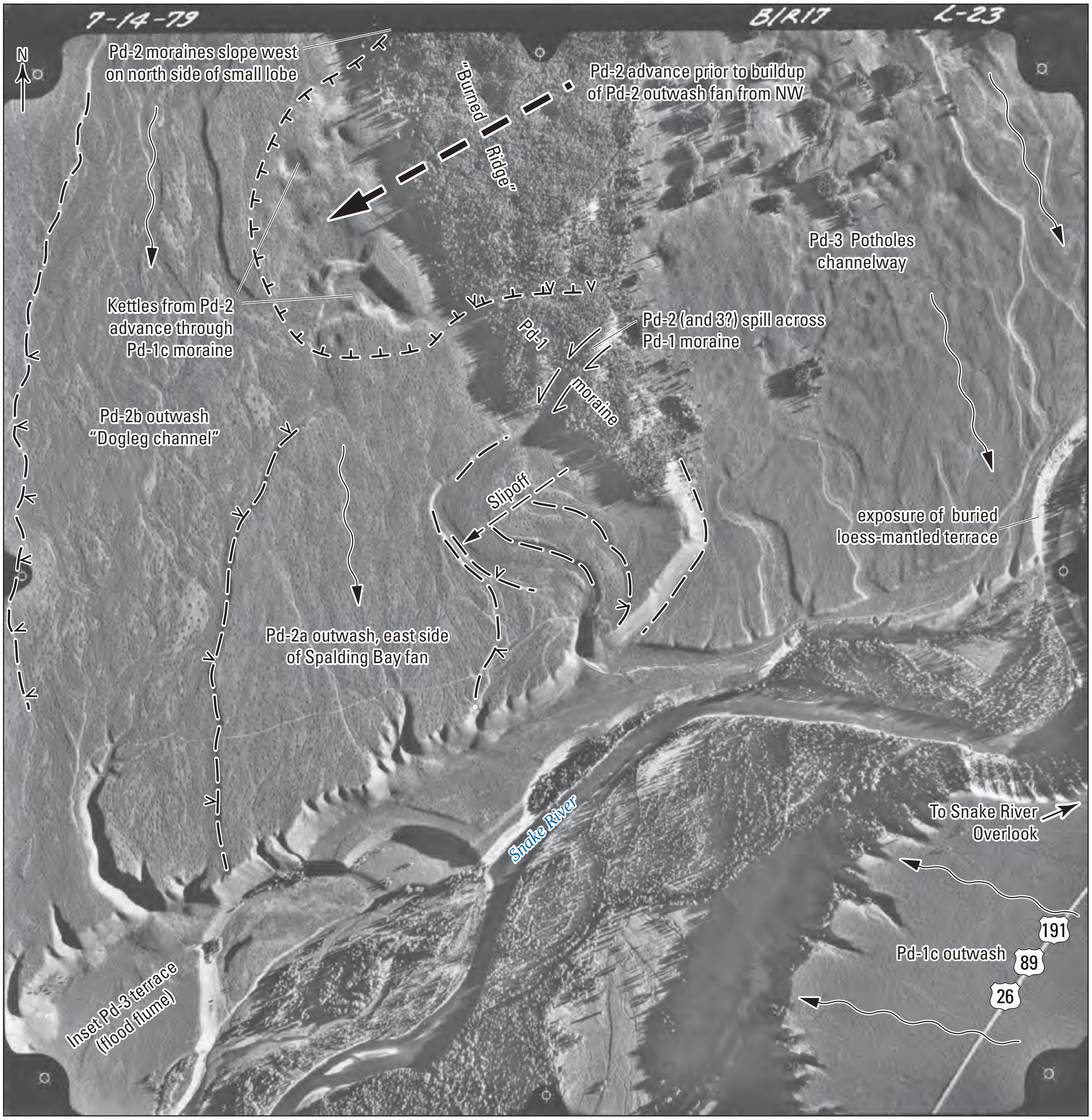
Pd-1 and Pd-2 Outwash Terrace Relations

As illustrated in the historic Ansel Adams black and white photograph from the Snake River Overlook area (fig. 29), outwash terraces form a dramatic foreground for the Teton Range. However, the upper terraces on both sides of the Snake River Overlook do not correlate as assumed by Love and de la Montagne (1956), Gilbert and others (1983), and Love and others (1992). Although the terrace treads on both sides of the river are at a similar height above the Snake River at this locality, they are of different age and from different sources. The Pd-1 outwash terrace slopes to the west, away from its source to the east, and projects beneath the Pd-2 terrace on the west side of the Snake River (figs. 29 and 32). In contrast, the Pd-2 terrace slopes southeast, away from its source to the northwest. The braided-channel pattern on the older Pd-1 terrace (fig. 22) is much more muted than that on the Pd-2 terrace across the river to the west (fig. 29), probably because of loess deposition on the Pd-1 terrace in Pd-2 time.

About 5 km south of Snake River Overlook in the area of the Teton Point Turnout, the Pd-2 Spalding Bay outwash fan overlaps and locally undercuts the Pd-1 outwash (fig. 31). The modern Snake River in this area is incised along the topographically low seam between these two outwash fans.

Farther East of the Snake River

Eastward from Hedrick Pond, the Pd-2 ice margin rises 50 m (160 ft) to 2,175 m (7,140 ft) to the top of “Spread Creek



Base photograph from Bureau of Reclamation, 1979

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EXPLANATION

Stream terrace scarp—V on younger side

Pd-2 advance through low in Pd-1c moraine—V on younger side. Hachures on Pd-2 side

Margin of meltwater channel

Outwash streamflow

Figure 29. Low sun-angle aerial photograph showing relations between Pd-1, Pd-2, and Pd-3 outwash terraces in the Burned Ridge-Snake River Overlook area. They are: (1) lower right, Pd-1c outwash with subdued channels preserved; (2) most of left half, Pd-2a outwash with moderately fresh channels and including the slightly younger "Dogleg Channel" (Pd-2b); and (3) upper right, Pd-3 outwash with fresh channels and abundant, deep kettles formed by buried Pd-2 ice blocks. Note also shallow kettles in Pd-2 outwash apparently resulting from early Pd-2 advance through the inferred paleo-topographic low in Burned Ridge landform shown in upper central part of photograph. The present Snake River is located where the Triangle X-2 lake spilled over the low point at the seam between the west-sloping Pd-1 outwash fan and the southeast-sloping Pd-2 outwash fan. Repeated floods lowered this outlet from an altitude of 2,085 meters (6,840 feet) to 2,048 meters (6,720 feet) in Pd-3 time.

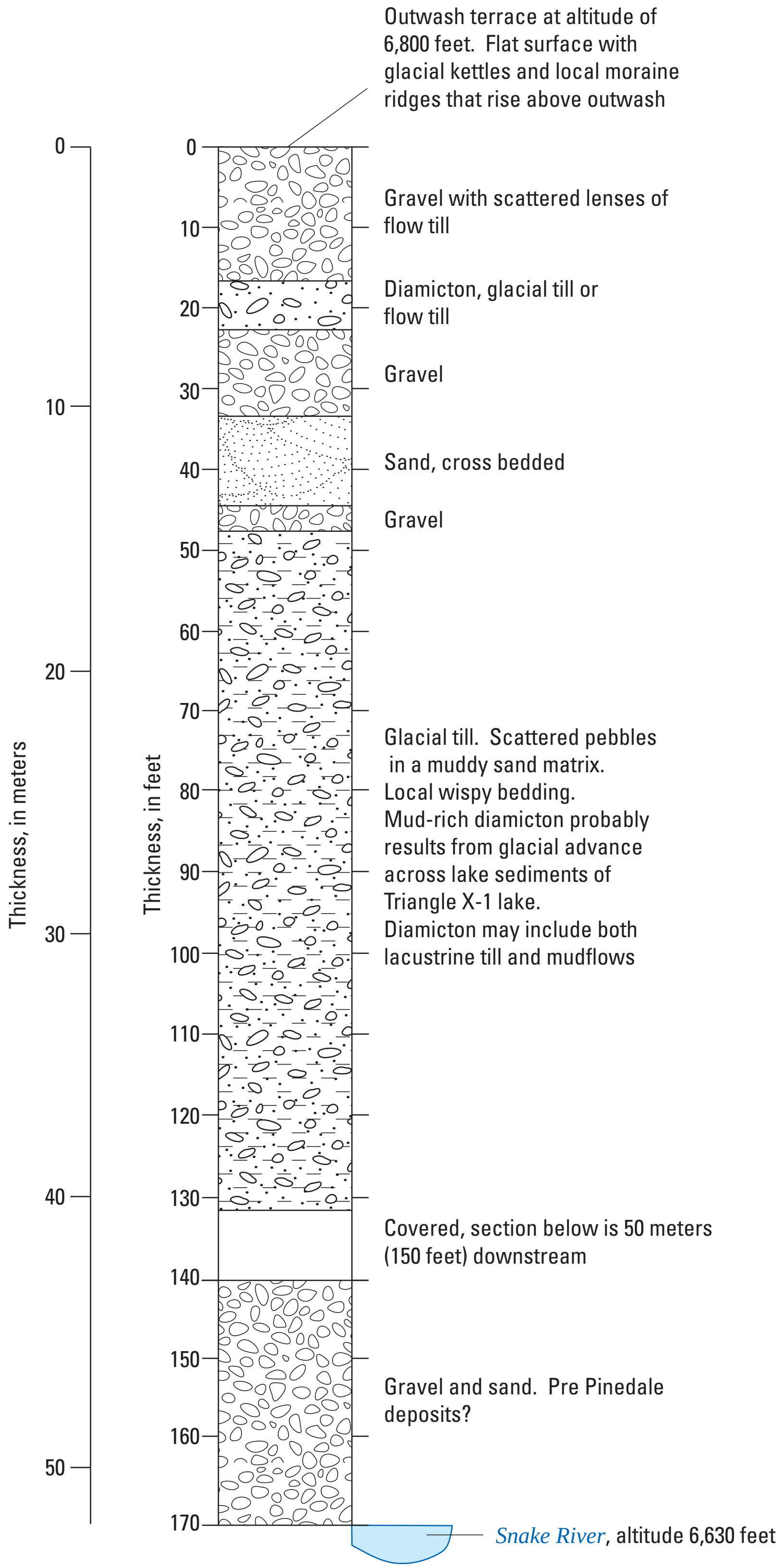

Figure 30. Mostly Pd-2 deposits of the Hedrick Pond bench. The main part of the section is a stone-poor glacial till rich in fines (silt, clay, and sand). The abundant fines are inferred to be from a low-gradient advance of ice across Triangle-X-1 lake sediments. The Hedrick Pod bench is a kettled outwash terrace with discontinuous morainal ridges up to 15 meters (50 feet) high that rise above the outwash.

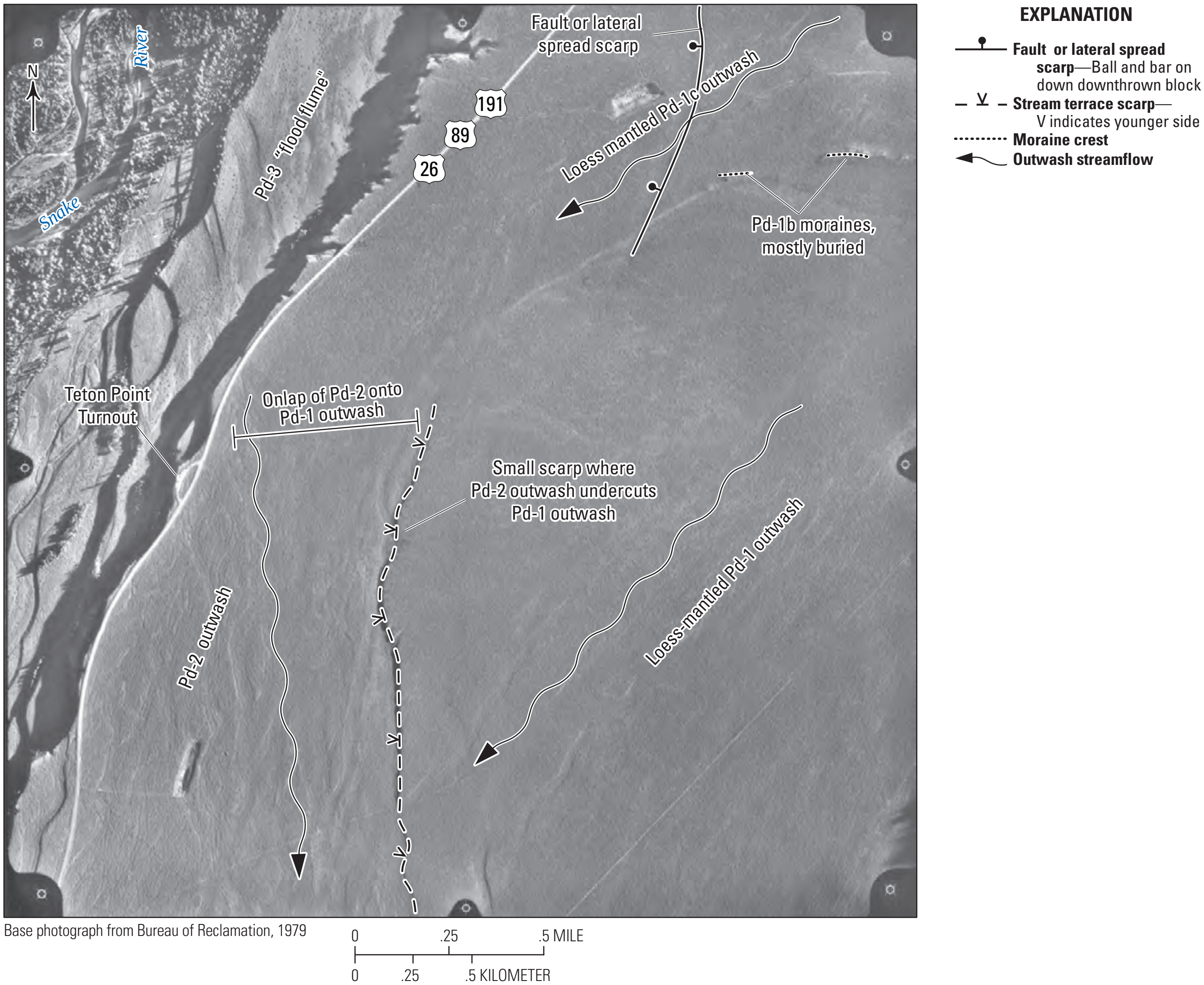

Figure 31. Low sun-angle aerial photograph showing onlap of Pd-2 outwash fan on southwest-sloping surface of Pd-1 outwash fan. In the lower half of the figure, the Pd-2 outwash stream has trimmed back the edge of Pd-1 outwash to form a low scarp.

hill" (fig. 4). On the north side of this hill, Pd-2 moraines actually descend to the east, indicating the Buffalo Fork lobe did not reach this area in Pd-2 time. On the south side of the Buffalo Fork valley, Pd-2 moraines and kame benches descend eastward up the valley, similar to the less extensive Pd-3 advance discussed in the section "Damming of Buffalo Fork." This Pd-2 backfill would logically be farther up the Buffalo Fork valley than the more clearly defined Pd-3 glacial backfill. A reasonable location for this Pd-2 glacial backfill is the moraine-mantled bedrock knob where the Turpin Meadow Road intersects U.S. Highway 287. In Pd-2 time, the terminus of the Buffalo Fork lobe was upvalley from here, and the Pd-2 Pacific Creek lobe may have then dammed the Buffalo Fork valley to an altitude of at least 2,135 m (7,000 ft).

The north side of the valley, from the Heart Six Ranch area to at least 7 km farther upvalley, preserves extensive deposits of kame benches and moraines that may be Pd-2 deposits of the Buffalo Fork lobe (fig. 4). A sediment trap between the Pacific Creek and Buffalo Fork glacial lobes appears responsible for these extensive glacial deposits.

The interfluve ridge on the north side of the Buffalo Fork valley clearly displays north-south streaming by the Pacific Creek lobe (noted later on figure 40). At this time, the Pacific lobe flowed south into the ice-free valley of Buffalo Fork.

Pd-2 Advance from Jackson Lake to Hedrick Pond Area

The low slope of the Pd-2 glacial advance from the present Jackson Lake area to Hedrick Pond area may reflect basal sliding across a wet, clay-rich deformable bed of Triangle-X 1 lake sediments. In the Hedrick Pond area 2.7 km east of the Snake River Overlook (fig. 4), the altitude of the Pd-2 terrace is ~2,085 m (6,840 ft) and Pd-2 ice filled the area to the northwest, making this a kame terrace. The glacier advance from the Jackson Lake area to the Pd-2 position near Hedrick Pond was about 7 km (4.3 miles), and the glacier surface may have risen about 100 m (300 ft) toward the north over this distance. Using the plot of Pierce (1979, fig. 48), a slope of 70 ft/mi and an ice thickness of 100 m (300 ft) yields a basal shear stress of about 0.1 bar. Mountain valley glaciers typically have a basal shear stress of 0.5 to 1.5 bars. This glacial reconstruction with a basal shear stress of 0.1 bars is only reasonable if the glacier was flowing on the wet, muddy, deformable bed, here thought to be the Triangle X-1 lake sediments.

Topography Between the Pd-1 and Pd-2 Advances

The paleotopography between the Pd-1 and Pd-2 advances is rather speculative, but given the great thickness and different locations of the heads of Pinedale Pd-1 and Pd-2 outwash fans, the topography before the Pd-2 advance probably differed significantly from the present topography. The Pd-1 outwash sloped to the west toward the paleo-Snake River and the paleo-Snake River was closer to the Teton Range front than the present position of the river (fig. 32). The Pd-2 outwash fan heads 80 m (260 ft) above Jackson Lake and kettles at the head of this fan extend to nearly the lake level (fig. 28). This kettle depth suggests that before Pd-2 time the land surface here may have been near the present-day lake level. The paleo-drainages of Pacific Creek, Buffalo Fork, and Spread Creek would have flowed farther west to join this paleo-Snake River. The location of paleo-valleys that may have channeled Pd-2 ice flow are: (1) kettles 37 m (120 ft) deep near the head of the Spalding Bay channelway (fig. 28); (2) kettles 30 m (100 ft) deep at Burned Ridge-Dogleg moraine reentrant (northeast end of outwash in fig. 24); and (3) the kettled topography east of the southern part of Burned Ridge (fig. 29). The west side of Spalding Bay exposes quartzite-rich gravel considered most likely of Pd-1 age, hence the Pd-1 ice margin was likely east of here.

Blackrock Meadows Area

A reasonable candidate for the Pd-2 ice margin is at the west end of Blackrock Meadows (fig. 21). There, a plug of glacial deposits about 40 m (125 ft) thick partially blocks the west end of Blackrock Meadows. This deposit is incised by Blackrock Creek to expose ice-dammed sediments of silts and sands with lesser gravel (fig. 33). Deltaic cross-bedding in the sands commonly dips east indicating deposition by an ice-marginal, south-flowing stream into a glacially dammed lake in the Blackrock Meadows area. Immediately to the west is a bulky moraine (fig. 33) that rises to the north across U.S. Highway 287 to the paved overlook. This prominent moraine continues to west along the north side of Flagstaff Creek that is inside of and recessional from the Pd-1 limit (fig. 21).

The moraine along Flagstaff Creek represents a significant recession in the source area of the Buffalo Fork glacial lobe, for in Pd-1 time ice at least 150 m (500 ft) thick flowed west out of Blackrock Meadows. This substantial reduction in size from Pd-1 to Pd-2 time in the Blackrock Meadows area is compatible with the large (20 km?) glacial recession of the Buffalo Fork lobe from Pd-1 to Pd-2 time.

In Blackrock Meadows, small, steep slab glaciers piled moraines of inferred Pd-2 or Pd-3 age on the flat valley floor at the base of the steep northwest slope.

Pinedale-3 Glaciation

Margin Just Beyond Jackson Lake

The Pinedale-3 ice margin of the Snake River lobe is most clearly represented by outwash fans that head just beyond the margin of Jackson Lake (fig. 34). The Pd-3 phase was previously called the Jackson Lake phase because the deposits are close to the margin of Jackson Lake (Fryxell, 1930; Love and Reed, 1968; Love and others, 1992; and Pierce and Good, 1992). The Pd-3 glacial outwash defines the margin of the Pd-3 glacier along the southern margin of the GYGS. Three of the outwash channelways were fed by the Snake River lobe and the Pacific Creek lobe fed the Cow Lake channelway. The four channelways are described from west to east.

Meltwater continued incision of the Spalding Bay channelway in Pd-3 time where the most incised Pd-3 channelway has a gradient of 6 m/km (fig. 28). Total incision of the Pd-2 fan head was about 30 m (100 ft) forming the flight of terraces shown in figures 26 and 28. Pd-3 meltwater flow continued south in a trench around the margin of the inner Jenny Lake moraines and farther south on the west side of Timbered Island to terraces west of Moose (fig. 34).

The Potholes outwash fan (figs. 35 and 36) heads at an altitude of ~2,103 m (6,900 ft) and was followed by about 20 m (70 ft) of fan-head incision. The altitude of the lowest, distal part of the outwash fan is 2,060 m (6,760 ft). From its lowest head altitude to lowest distal margin, the gradient was exceptionally low at 4.4 m/km (23 ft/mi). This outwash buried many ice blocks of Pd-2 age that are aligned east-west parallel to the inferred margins of the retreating Snake River lobe. The outwash prograded southeastward into the Triangle X-2 lake as discerned from exposures in the bluffs above the Snake River; here, outwash gravels overlie poorly consolidated lake silts. Although these gravel-capped bluffs may be mistaken for a terrace associated with the Snake River, this is unlikely to be the case for there is no corresponding terrace on the east side of the river and the flow of the depositing stream was perpendicular to the Snake River rather than parallel to it.

The South Landing outwash fan heads with paleo-outwash channels up to 100 m wide and an altitude as high as ~2,100 m (6,890 ft) (fig. 37). Fan-head incision is only 10 m (30 ft). Farther downstream, the channels bifurcate multiple times (fig. 37) indicating the outwash load filled channels to

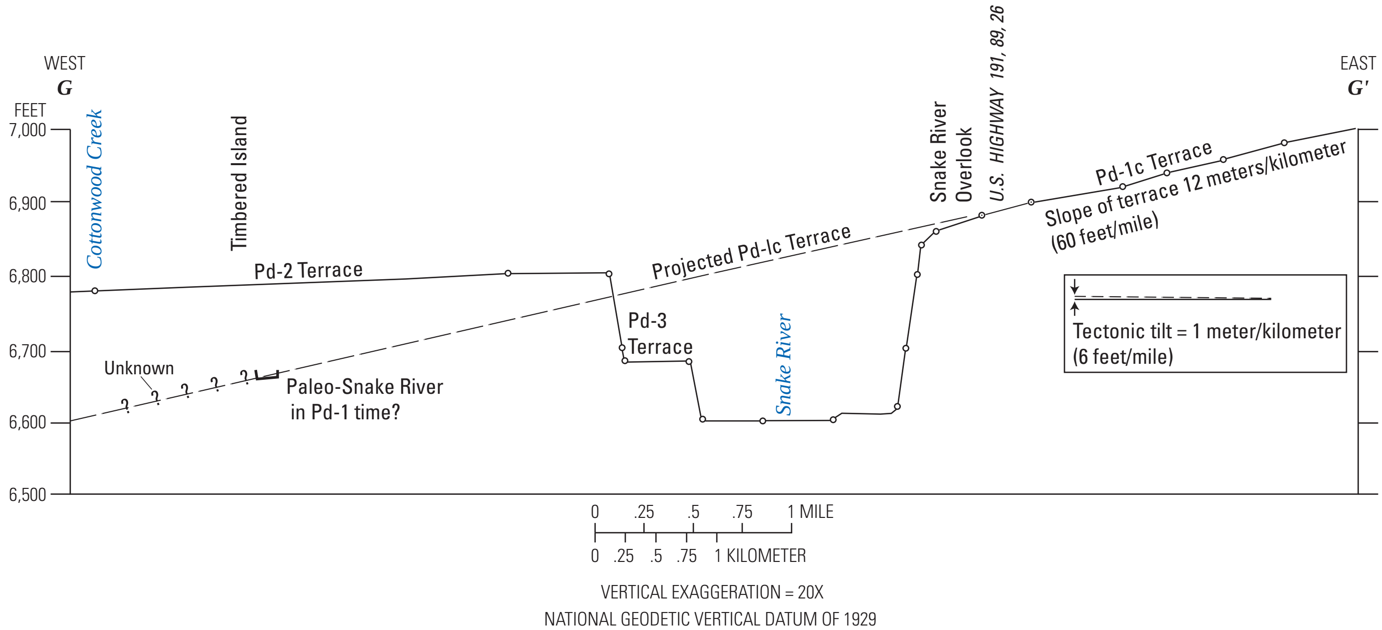

Figure 32. East-west profile (Section *G–G′* in figure 4) drawn one kilometer south of the Snake River Overlook showing that the west slope of Pd-1 terrace projects beneath, and is buried by the Pd-2 terrace. The Pd-1 terrace slopes to the west at 12 meters per kilometer (60 feet per mile) and projects below the Pd-2 terrace on the west side of the Snake River. Although the Pd-1 and Pd-2 terraces are at a similar altitude in the Snake River Overlook area, they do not correlate as commonly assumed. In Pd-1 time, the topography was lower than present westward toward the Teton Range and the Teton fault. The Pd-1 outwash would have joined the south-flowing Snake River someplace east of the Teton Range and it may have been just east of Timbered Island. The westward slope of Pd-1 terrace has only a minor component (less than 10 percent) of a tectonic tilt compared to the original depositional slope (see “Pinedale Terrace and Outwash Relations).

produce this braided-channel pattern. The South Landing fan differs from The Potholes outwash fan in being nearly kettle-free, except where it buried blocks of Pd-3 ice of the Pacific Creek lobe at the distal ends of the combined South Landing-Cow Lake outwash fans. This outwash fan prograded into the Triangle X-2 lake in a fashion similar to The Potholes outwash fan described above. It has a relatively low gradient of 5.3 m/km (30 ft/mi).

Insight into the meltwater-sediment system beneath the glacier stems from observations between the present Jackson Reservoir level and the ice margin at the head of the South Landing channelway. Reservoir-shore bluffs expose esker-like ridges of gravel with a sand matrix and some gravel imbrication suggesting flow to the southeast away from the glacier (fig. 38). These ridges are up to 10 m (30 ft) high and climb upward towards the Pd-3 glacier margin at the head of the Pd-3 outwash (fig. 38). No single gravel ridge can be traced all the way from the reservoir level to the head of the outwash fan, but three of the esker ridges are traceable for more than 100 meters. These climbing eskers apparently result from subglacial channels transporting stream gravel driven by hydraulic pressure up to the head of outwash at the glacier snout, where they may have resulted in hydraulically pressurized “fountains” of meltwater. Assuming these subglacial meltwater channels extended farther northward at the base of the glacier; they could have hydraulically eroded the glacier bed (Booth and Hallet, 1993; Stucki and others, 2010), and may have contributed significantly to the deep excavation of Jackson Lake.

The Cow Lake channelway (fig. 34) heads at altitudes of ~2,110 to 2,088 m (6,920 to 6,850 ft) and flows south. This channelway was the only one fed by the Pacific Creek lobe. The western sector of the Cow Lake channelway is undercut by the South Landing fan, making this sector slightly older. Abundant kettles at the eastern confluence of the Cow Lake and South Landing fans demonstrate burial of ice from the Pacific Creek lobe. These kettles contain calcareous lake sediments with snail shells that have an uncalibrated radiocarbon age of 9,000 years (Love and Reed, 1968). Although this was once thought to date the glacial deposits, field examinations show these are kettle-fill sediments are of post-glacial age.

Drumlinoid Topography East of Jackson Lake

East of the middle third of Jackson Lake, in the area of Colter Bay, is a large tract of terrain formed by basal sliding of the glacier to the southeast (fig. 39). Here, the Snake River lobe overrode and streamlined older deposits of till and outwash in both Pd-2 and Pd-3 time. The sculpted deposits are rich in Pinyon-type quartzite roundstones carried into the area by the Snake River lobe in Pd-1 time. In the elongate depressions formed by the southeast glacial overriding and sculpting are many of the bays of Jackson Lake as well as ponds and wetlands.

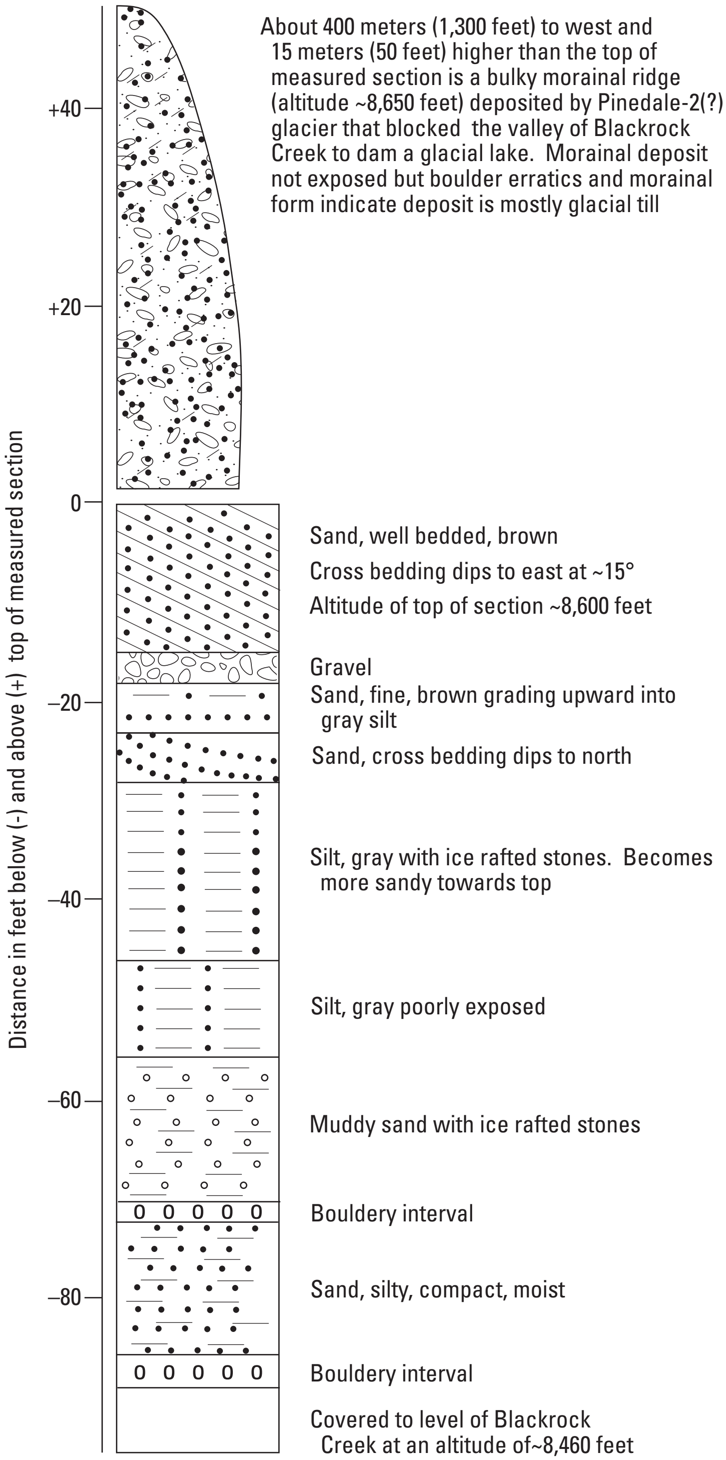

Figure 33. Glacially dammed lacustrine, deltaic, and ice-contact deposits of Pd-2 age at the northwest end of Blackrock Meadows. The location of this section is shown in figure 21. The moraine in the upper part of figure 33 was deposited along the southern margin of the Buffalo Fork lobe. This glacier dammed a lake in BlackRock Meadows and these sediments were deposited adjacent to this glacier in that lake. The Pd-2 glaciation here was less extensive that that of the Pd-1 glaciation (fig. 21) when a glacier about 200 meters (600 feet) thick flowed west out of the Blackrock Meadows area and left striations on bedrock that trend N. 85° W.

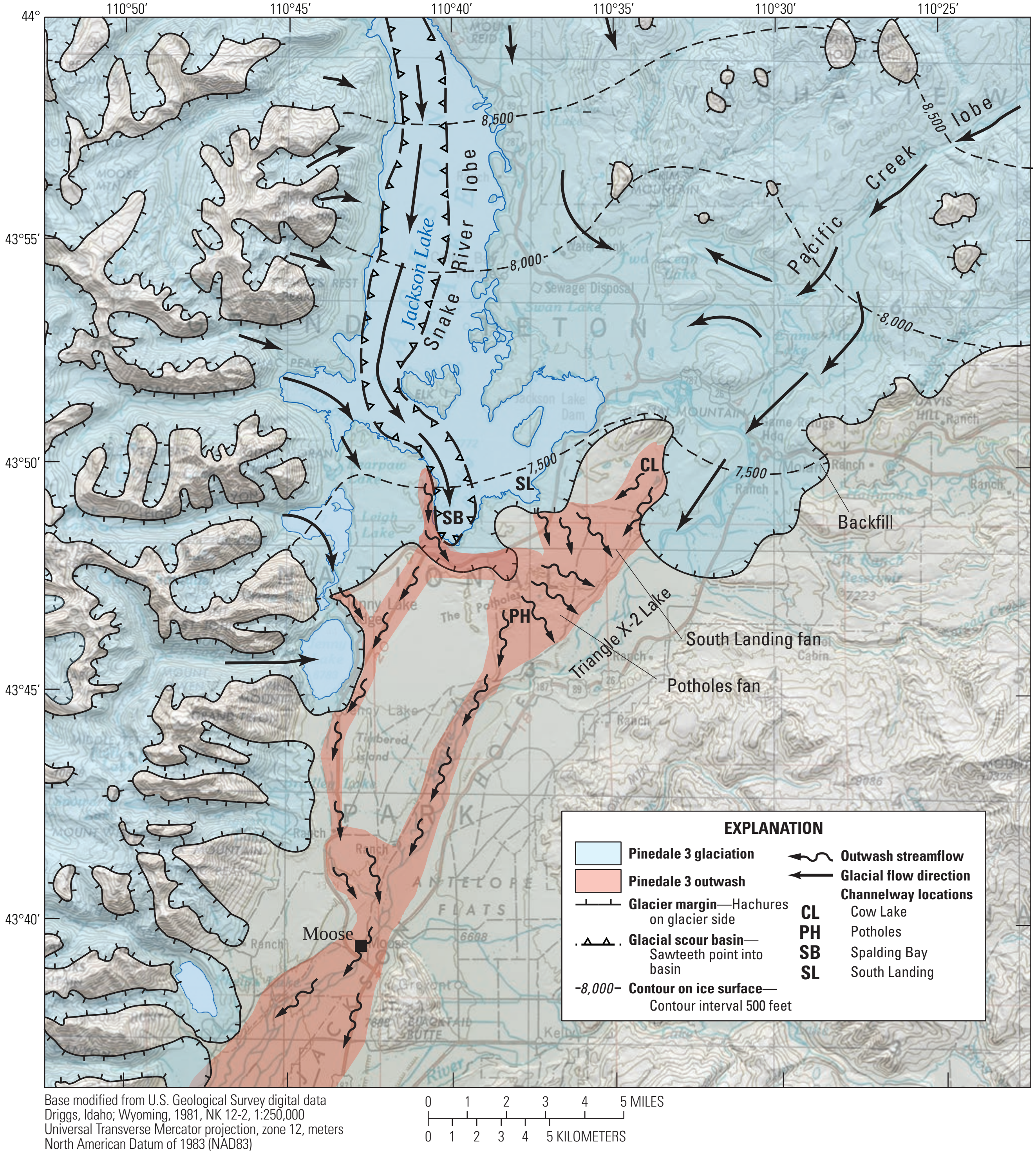

Figure 34. Pd-3 glacier extent and associated outwash. The main difference between Pd-2 and Pd-3 is the recession of ice from the Triangle X-2 basin which opened this area for the deposition of extensive outwash of The Potholes, South Landing, and Cow Lake fans. Jackson Lake continued to be scoured and eroded by the Snake River lobe and sediment was delivered to the glacier margin to build gravelly outwash fans.

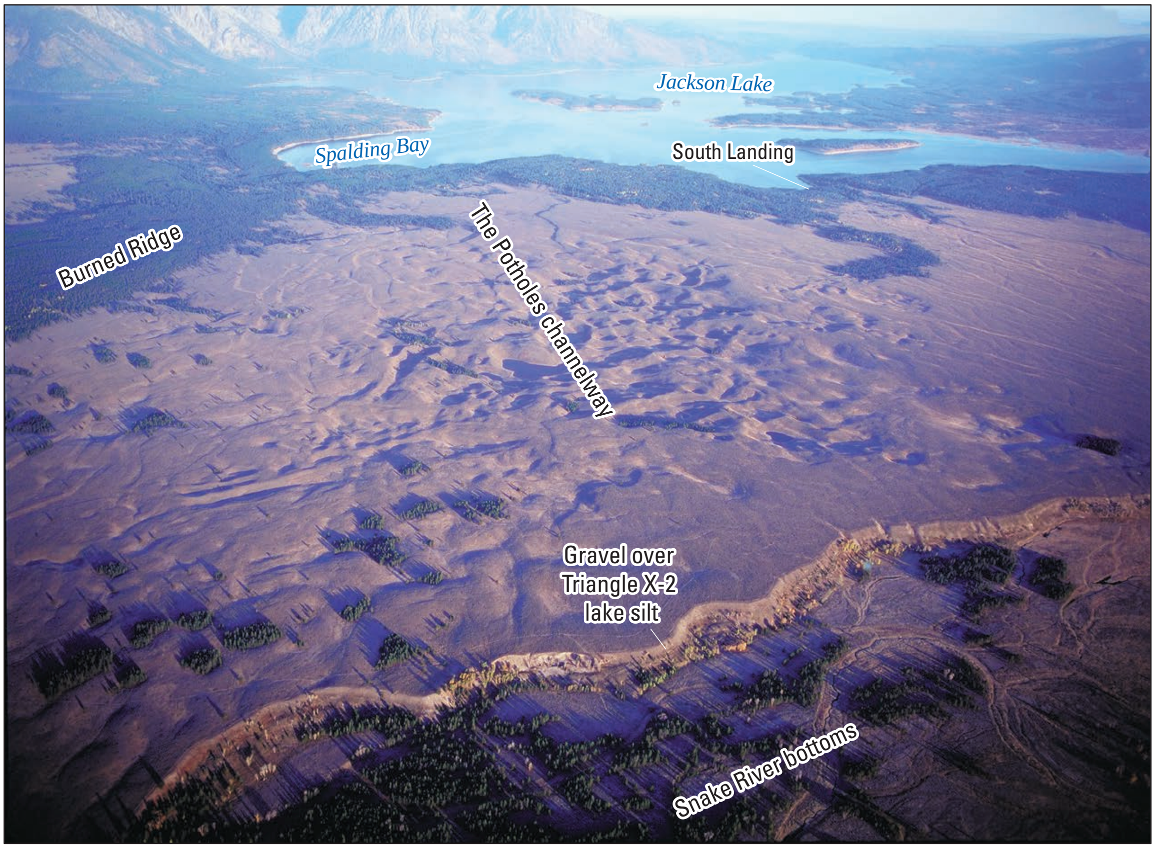

Figure 35. Pd-3 Potholes channelway. The Snake River bottoms are in the foreground above which are exposed Triangle X-2 lake sediments overlain by Pd-3 outwash gravel. The kettles are aligned perpendicular to the radius of the fan and are interpreted to be recessional blocks of the Pd-2 glacier that flowed southeast from the Spalding Bay. Oblique color aerial photograph by Michael Collier of Flagstaff, Arizona.

Damming of Buffalo Fork

During the Pd-3 glacial phase, the east side of the Pacific Creek lobe flowed up the lower valley of the Buffalo Fork and blocked the drainage (fig. 40). The Pd-3 ice surface of the Pacific Creek lobe was similar to but at a lower level than the Pd-2 ice described earlier. This lobe constructed ridges and furrows of glacial till and gravel that arc (protrude) up the valley of Buffalo Fork. Just upstream from the Pd-3 deposits that blocked the Buffalo Fork valley near the Grand Teton National Park boundary, Pd-3 lake sediments on recessional kame gravels demonstrate a glacial dam of the lower Buffalo Fork valley. The uplands on the north side of this backfill display prominent south-flowing glacial scour of the Pacific Creek lobe at a time when the glacier in this part of the Buffalo Fork valley had receded (fig. 40).

Relations of Pacific Creek and Snake River Lobes

At the west end of Emma Matilda Lake (fig. 4), a two-sided kame terrace indicates the coexistent location of the Snake River and Pacific Creek lobes during the recession from the Pd-3 position. The kame gravels are at an altitude of 2,120 m (6,960 ft) and accumulated in the space between the Pacific Creek lobe which occupied the Emma Matilda Lake area and the Snake River lobe which occupied the Christian Pond area to the west. At the west end of Two Ocean Lake (fig. 4), a similar two-sided kame terrace at an altitude of 2,195 m (7,200 ft) indicates the simultaneous location of the same two lobes. Although they are not at the maximum Pd-3 position, these two-sided kame terraces clearly demonstrate simultaneous position of the Snake River and Pacific Creek lobes.

Glaciofluvial Activity of the Snake River in Pd-3 Time

In Pd-3 time, the location of the Snake River downstream from the Snake River Overlook was along the topographic low formed along the seam between the conical forms of the Pd-1 outwash fan from the east and the Pd-2 outwash fan from the northwest (fig. 20). A high terrace of the Snake River is at the outlet of the Triangle X-2 lake (altitude ~2,073 m, ~6,800 ft) just north of and below the Snake River Overlook. This outlet was then progressively incised 25 m (80 ft) to about 2,048 m (6,720 ft) as the 12 km long downstream ramp was eroded. Because the outflow of the Triangle X-2 lake contained no bed load of gravel, the only bedload was derived from flow

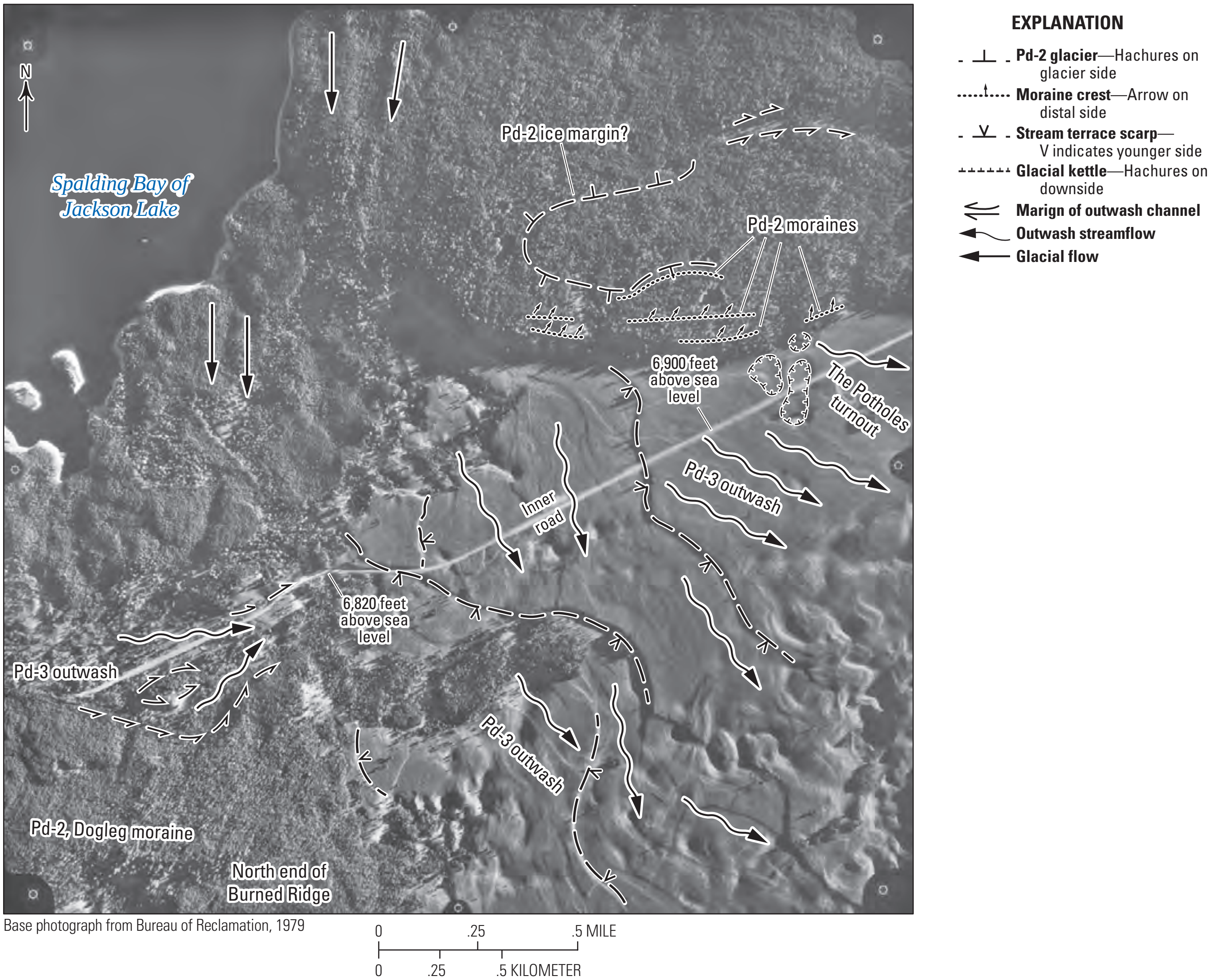

Figure 36. Low sun-angle aerial photograph showing glacial geologic relations near the head of The Potholes channelway. The head of the channelway is 52 meters (170 feet) above the natural level of Jackson Lake. This Pd-3 channelway is characterized by abundant kettles. The arcuate scarps at the edge of Pd-3 stream channels are shown by carets on the younger channels. In the forested area on the east side of the channelway are Pd-2 morainal ridges shown by dotted lines. These moraines slope to the east and are asymmetric with a steeper, cobbly proximal side and a gentle distal side (Pierce and Good, 1992, Stop 2-2). A Pd-3 outwash bench slopes eastward from the Spalding Bay channelway to The Potholes channelway which is now followed by the highway.

downstream from the outlet. Aided by large floods from the glacially dammed lake in the Buffalo Fork valley, the Snake River outflow was able to progressively incise 25 m (80 ft). We call this the “flood flume” (fig. 20). The prominent inset terrace about halfway from the upper outwash level to the present Snake River represents a later episode of one of many floods that probably occurred. It displays large-scale bed forms created by floodwaters perhaps 5 to 8 m (15 to 25 ft) deep and 1.5 km wide. Longitudinal, flow-parallel flood bars occur along the valley wall as high as the level of the Pd-2 terrace (see ahead to fig. 42 in section Pinedale Terrace Profiles and Outwash Relations). These small bars are very stony, well sorted, and well drained as indicated by cactus plants.

Pinedale-3 Lakes

Triangle X-2 Lake

In the Triangle X Ranch area, deltas of ash-rich, recycled Teewinot Formation were built into the Triangle X-2 lake. At least four deltas are observed between altitudes of about 2,080 to 2,048 m (6,820 to 6,720 ft) (fig. 41). The lowest delta is visible from the highway as badlands terrain in white ash (Pierce and Good, 1992, Stop 1.6, p. 21). Additional lake sediments are exposed west of the Snake River beneath the outwash fan gravels of The Potholes and South Landing channelways. These gravels were built southeastward into the Triangle X-2 lake.

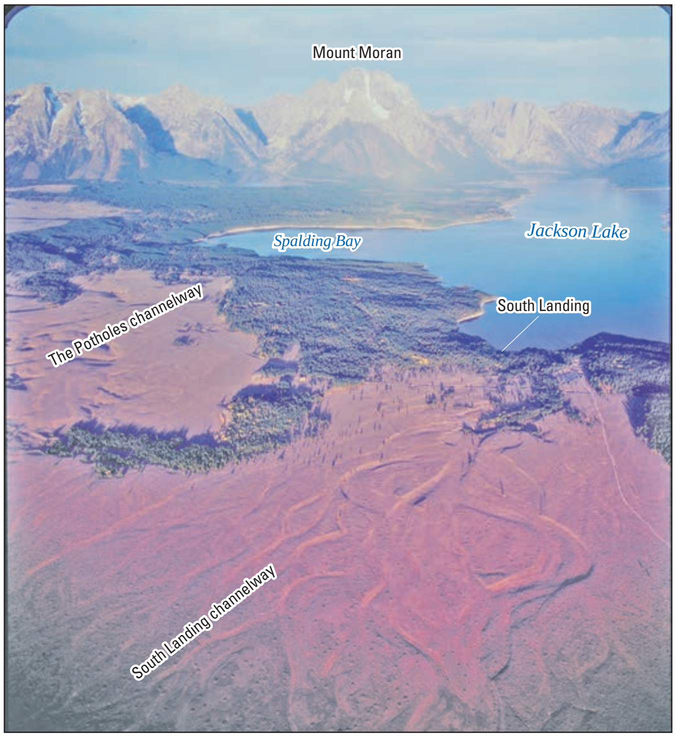

Figure 37. Pd-3 South Landing channelway. This channelway heads 40 meters (130 feet) above the natural level of Jackson Lake and contrasts with The Potholes channelway in being nearly free of kettles, except in its lower, easternmost part. Note the preservation in detail of arcuate scarps of the edge of the Pd-3 outwash stream. Oblique color aerial photograph by Michael Collier of Flagstaff, Arizona.

Oxbow Lake

Immediately downstream from Oxbow Bend (fig. 4), a sandy lacustrine bar of Oxbow lake spans nearly the entire floor of the Snake River valley to an altitude of 2,075 m (6,800 ft). The bar is inside and younger than the maximum extent of Pd-3 ice. This sand bar slopes about 6 m (20 ft) from north to south over a distance of 1 km. The bar consists mostly of unconsolidated, well sorted sand and contains pebbles towards its northern end. Lake sediments are exposed in the bluffs of the Snake River between this bar and Pacific Creek. About a kilometer north of Moran Junction (fig. 4), sediment benches interpreted to be deltaic deposits occur also at an altitude of 2,075 m (6,800 ft).

Pd-1, Pd-2, and Pd-3 Moraines on Signal Mountain

Signal Mountain (fig. 4) is near the southern margin of glacial lobes of the GYGS and recorded the successive lowering of the ice surface in Pd-1, Pd-2, and Pd-3 time. The slopes of Signal Mountain are draped with glacial moraines from all three phases of the Pinedale, although their exact configuration has proved difficult to unravel. Moraines on the northwest side of the mountain descend to the southwest and abruptly terminate into space at altitudes of ~2,286 to 2,165 m (7,500 to 7,100 ft). Ice surface contours and relations to outwash levels suggest roughly the following altitudes for the different Pinedale stages on Signal Mountain:

- Pd-1: ~2,377 m (7,800 ft), about 60 m (200 ft) above the 2,314 m (7,593 ft) summit of Signal Mountain;
- Pd-2: ~2,274 m (7,460 ft) on northeast part of Signal Mountain with recessional moraines to ~2,165 m (7,100 ft); and
- Pd-3: ~2,134 m (7,000 ft) and lowering to 2,115 m (6,940 ft) above South Landing channelway.

Pinedale Terrace Profiles and Outwash Relations

Profiles of the Pinedale terraces increase dramatically in height above the Snake River as the Pinedale glacial moraines are approached (fig. 42). The profiles are based on a line of projection that trends upstream along the Snake River from

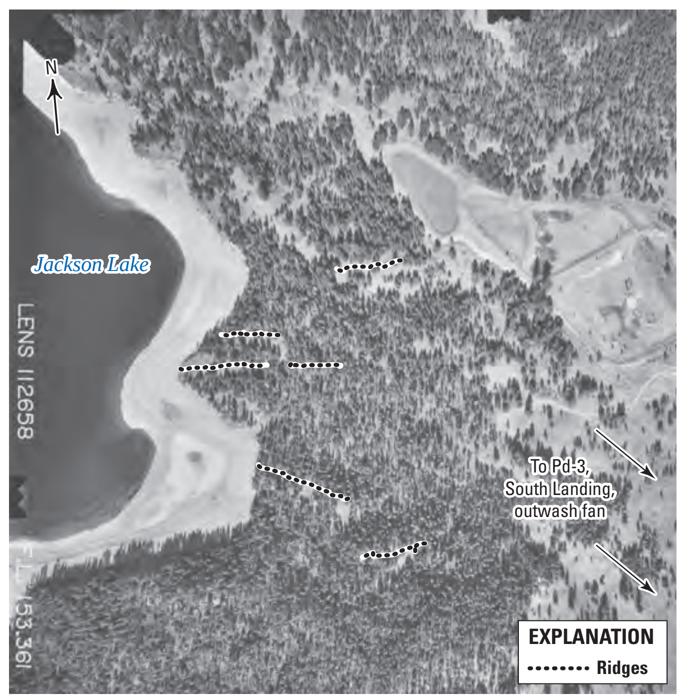

Figure 38. Esker-like ridges below and up-flow from the head of the South Landing outwash fan. These ridges are indicated by dotted lines and are somewhat discontinuous, but as a group ascend up to the head of the Pd-3 South Landing outwash fan. Exposures in lake-shore bluffs show the ridges consist of alluvial gravel. These climbing, esker-like gravel ridges indicate that confined, hose-like subglacial streams probably helped erode the glacial bed.

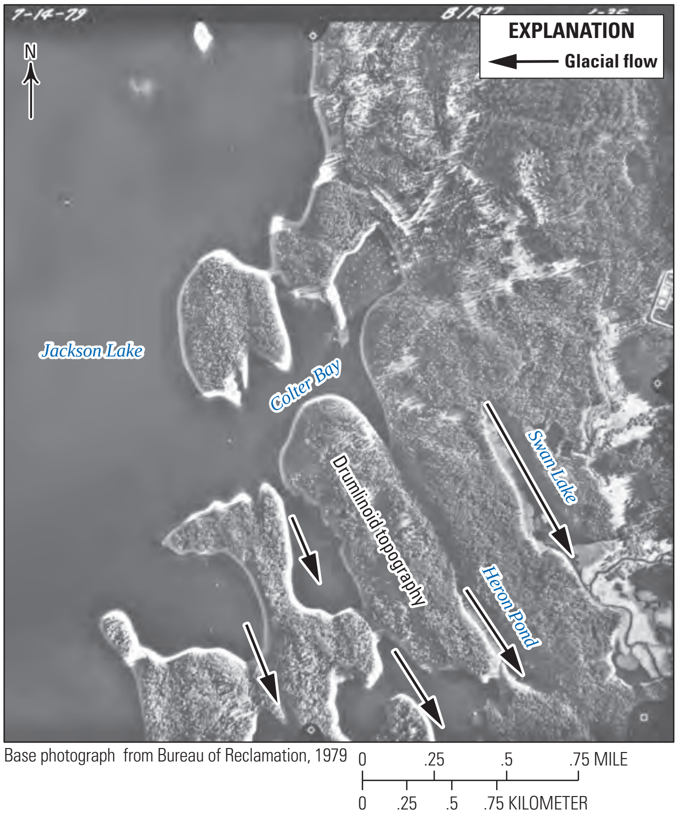

Figure 39. Drumlinoid topography along the east side of Jackson Lake. The smooth ridges and furrows were formed by basal sliding of the Snake River lobe to the south-southeast in Pd-2 and Pd-3 time. At the same time the Snake River lobe also scoured out the Jackson Lake basin. In addition to subglacial deposition of till, the Snake River lobe overrode and streamlined older deposits of outwash and till rich in quartzite and poor in rhyolite was most likely deposited in Pd-1 time by the Pacific Creek lobe. In this same area, four northeast-trending escarpments down to the northwest may indicate pre-Pinedale faulting in that no post-glacial scarps were observed.

below the town of Wilson to a position halfway between Moose and the Snake River Overlook (fig. 4, Line *A–B*). There, the profile splits into three branches as follows: (1) Line *B–C* (fig. 4) that extends northeast radially up the conical Pd-1c outwash fan (Antelope Flats) to the ice marginal channel along the south side of the Buffalo Fork glacial lobe (fig. 42, blue); (2) Line *B–D* (fig. 4) that continues north-northeast up the present Snake River and shows the Pd-3 incised terrace (fig. 42, green); (3) Line *B–E* (fig. 4) that extends north across Baseline Flat and up the Pd-2a outwash fan (red) to its head in Pd-2a moraines (fig. 42, red). The heads of Pinedale outwash rise to more than 110 m (350 ft) above the present Snake River, but downstream 42 km (26 miles) converge to only 3 m (10 ft) above the river (fig. 42). The maximum fill terraces have an overlapping “shingle” pattern such that, from upstream to downstream, the highest terrace surfaces are expressed as a succession from Pd-1 to Pd-2 to Pd-3, and therefore become younger downstream (figs. 18 and 42).

Pd-1c is the highest terrace, and it forms a conical outwash fan subtending an arc of 90° that slopes to the west and south. Pd-1c is the youngest of three Pd-1 outwash deposits that head where the gravel-laden, ice-marginal paleo-Spread Creek spilled out onto the east side of Jackson Hole. Channel patterns on the Pd-1 outwash surfaces are much more muted than those on Pd-2 surfaces, as seen on aerial photographs (figs. 22, 30, and 31), at least in part because of loess deposition.

Although some have concluded the west slope of the northern part of the Pd-1 terrace is tectonic (Love and de la Montagne, 1956; Smith and others, 1993b), the depositional slope for this section of the terrace is westward as indicated by the stream-channel pattern (figs. 22 and 32). The westward depositional slope (10 m/km; 60 ft/mi) of this outwash is much greater than the comparatively low westward tectonic tilt estimated to be only 1 m/km (6 ft/mi) based on the following. The post-glacial offset on the central part of the Teton fault is about 15 m (Gilbert and others, 1983; Byrd and others, 1994). Using the tilting measured from the 1983 M 6.9, Borah Peak earthquake as a reference (Stein and Barrientos, 1985), the 15-m post-glacial offset on the Teton fault is about 10 times the 1.45 m offset on the Borah Peak earthquake. At a distance of 10 km from the Borah Peak fault, tilting was 0.07 m/km. Ten times this for Antelope Flats is 0.7 m/km. The 21 ka estimated age of the Pd-1 outwash is 1.5 times the 15 ka age of post-glacial offset on the Teton fault. Thus, westward tectonic tilting of the Pd-1 outwash is roughly 1 m/km (1.5 × 0.7 m/km) (fig. 32). Therefore, the tectonic tilt is only about 10% the present slope and difficult to distinguish from the depositional slope.

On the east side of the Snake River at kilometer 8 (mile 5) (fig. 42), the Pd-1c outwash fan is overlapped and buried by the Pd-2 outwash (fig. 31). This location is adjacent to the Teton Point Turnout (fig. 31). There, the following patterns apparent on aerial photographs (fig. 31) indicate the Pd-2 is younger and from a more northerly source than the Pd-1c terrace: (1) paleo-channels have a fresher appearance and well-preserved depositional micro-topography; (2) paleo-channels have a southerly trend compared to the southwest-trending Pd-1c channels; and (3) a low scarp is formed where Pd-2 streams undercut Pd-1 outwash. On figure 42, the Pd-2 outwash terrace (red line) is shown as descending to the Pd-1 outwash surface (blue line) and farther south burying the projection of Pd-1 outwash (dashed blue line).

The Pd-2 terrace has a lesser slope than the Pd-1c terrace (fig. 42). This suggests that it had a larger discharge-to-load ratio and probably carried more of the overall drainage of Jackson Hole than did the Pd-1c outwash across Antelope Flats. This seems reasonable, for when the Pd-1c outwash was deposited across Antelope Flats, the main southerly Snake River drainage was farther west. Such a paleotopography is also indicated by the projection of Pd-1c beneath Pd-2 and diagrammed for an east to west section in figure 32.

The Pd-2 outwash fan extends relatively unbroken on both sides of the Snake River from Teton Point Turnout to Moose (on figure 42, kilometer 8 to 16, mile 5 to 10), where it is the

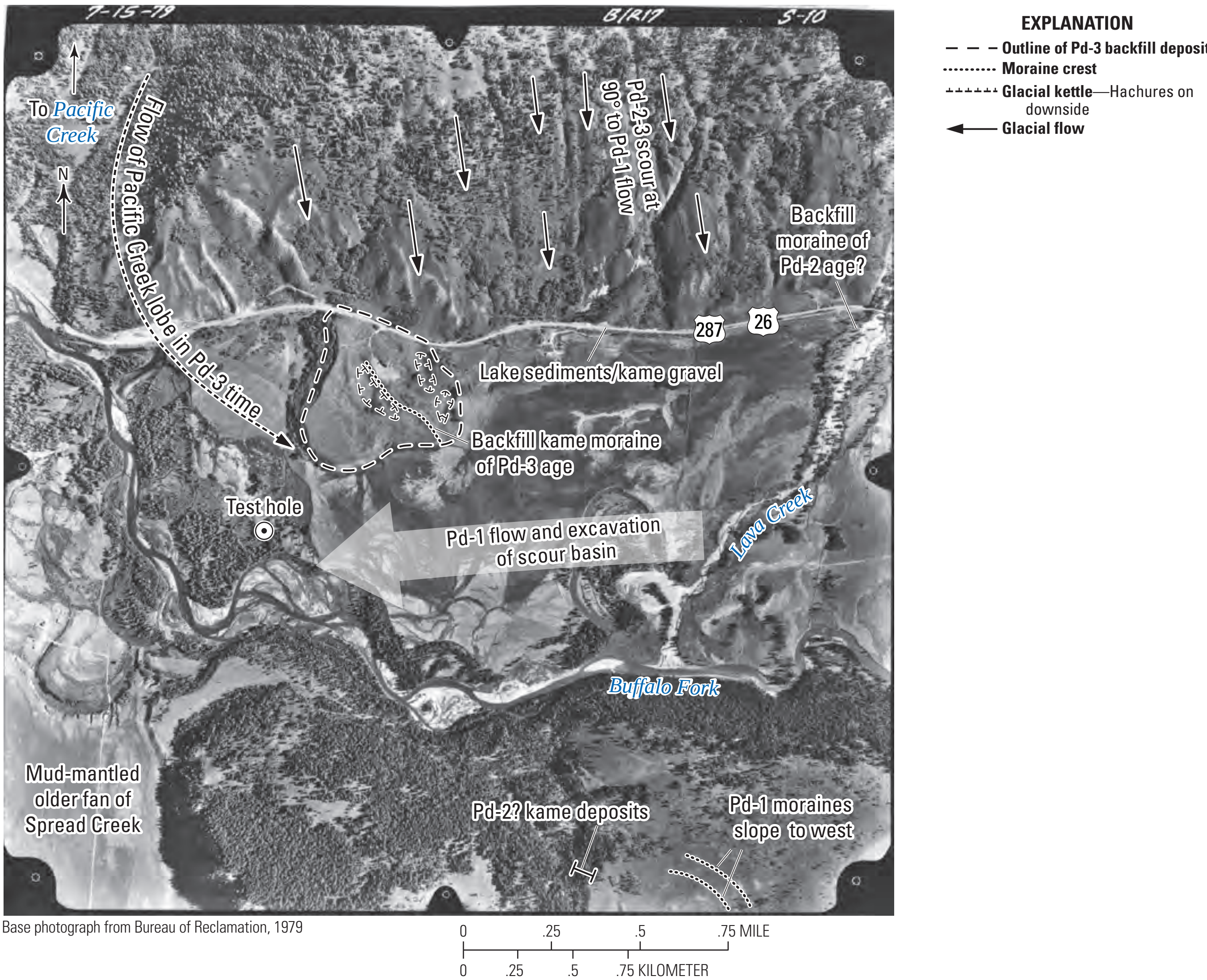

Figure 40. Lower Buffalo Fork valley showing plug of Pd-3 gravelly morainal backfill of the Pacific Creek lobe that advanced up the Buffalo Fork valley. Just upvalley from this plug are lake sediments overlying kame gravels. The upland in the northern third of the photograph shows intense southward glacial scour by the Pacific Creek lobe; this indicates the Buffalo Fork glacial lobe had receded upvalley by this time. For the test hole, McGreevy and Gordon (1964) report lacustrine (?) deposits from 13 feet to a total depth drilled of 52 feet.

maximum fill terrace. On the northern end of Blacktail Butte, a small remnant of the maximum fill terrace is preserved in a reentrant trimmed back by a scarp ~7 m (20 ft) high.

During Pd-3 time, stream level and gravel deposition changed dramatically along the length of the Snake River in Jackson Hole. The Pd-3 Potholes and South Landing outwash fans were built into the Triangle X-2 lake. These outwash fans head at the Pd-3 glacial margin and were built in the space that had been previously occupied by the Pd-2 ice advance.

From the Snake River Overlook to Moose, the Pd-3 strath terraces of the Snake River are inset into higher, older Pd-1 and Pd-2 terraces (fig. 42, kilometer 3 to 16, mile 2 to 10 miles, green lines). The head of this reach was the outlet of the Triangle X-2 lake, with a spill point that started at an altitude of ~2,085 m (6,840 ft) and eroded down to ~2,060 m (6,760 ft). South of the Triangle X Ranch, deltas rich in recycled ashy Teewinot Formation record a similar lowering of the Triangle X-2 lake from an altitude of 2,080 to 2,048 m (6,820 to 6,720 ft) (fig. 41).

Along the Snake River between Deadmans Bar and Moose, the Pd-3 terrace level is best displayed as the prominent strath terrace about halfway between the maximum fill level and the present river level (fig. 42). However, additional Pd-3 terrace remnants also occur both above and below this level. In detailed cross-valley profiles, R.A. Marsden (written commun., 2009) recognized about seven terraces between the Snake River and the top of the highest fill terrace (either Pd-1 or Pd-2), and many of these intermediate level terraces record incision in Pd-3 time. Incision of as much as 30 m (100 ft)

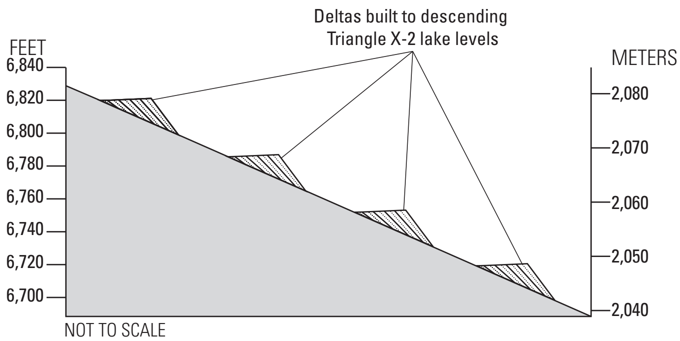

Figure 41. Sequence of deltas built near the Triangle-X Ranch in Pd-2 and Pd-3 time as the outlet of the Triangle X-2 Lake lowered. The lowering of the outlet of the Triangle X-2 lake required erosion of the more than 12-kilometer (7-mile) long gravel ramp from the Snake River Overlook area to beyond Moose (fig. 4). The deltas are rich in recycled white ash; eroded from the Teewinot Formation, which is exposed high on the slopes south of the Triangle X Ranch.

occurred from the maximum Pd-2 fill level down to the prominent Pd-3 terrace (fig. 42; blue bar at top with dashed blue arrow extending down to the prominent Pd-3 terrace).

Multiple floods aided the incision from the Pd-2 terrace level to the prominent Pd-3 inset terrace (fig. 42, dashed blue arrow) of the “flood flume” from kilometer 3 to 16 (mile 2 to 10). Several well-drained longitudinal gravel bars occur along the valley walls in this stretch, and large-radius channel scrolls occur on the surface of the prominent Pd-3 terrace. The outflow waters from Triangle X-2 lake would have started out with only a load of glacial flour (no gravel) but flows, especially floods down the initial surface (aqua bars on fig. 42), had a steep gradient of 14 m/km and were able to entrain gravel and erode a trench to form the “flood flume” in this inset valley which is only 1–2 km wide (0.6–1.2 miles). In contrast, the valley floor downstream from mile 10 has a slope of 6 m/km and widens to more than 5 km (3 miles) near the Jackson Hole Airport at mile 14. This lower slope and wider valley downstream from the flood flume evidently resulted in early Pd-3 floods washing across the terrace surface on which the Jackson Hole Airport is built (fig. 42). From the bedrock “anchor” of Blacktail Butte, the scarp has a smooth low-curvature arc interpreted to have been undercut by large floods of Pd-3 age (fig. 13).

In addition to the spreading out and decrease in gradient of waters downstream from the flood flume, other features also suggest floodwaters covered the terrace on which the Jackson Hole Airport is built. Between kilometer 14 and 19 (mile 9 and 12) of figure 42, the erosional eastern margin of such floods was guided by the fluvially trimmed bedrock scarps along the west side of Blacktail Butte. Compared to the smooth, gradual arc shown in figure 13, a normal outwash braided stream would be expected to have eroded a more embayed scarp where channel loops have undercut the scarp. For example, the braided-channel pattern of the Pd-2 outwash surface has a radius of ~300 m (fig. 31) whereas the radius of the arcuate terrace scarp east of the airport is more than 15 km (fig. 13). This supports scarp undercutting by floods rather than by a typical braided outwash stream.

Farther downstream in the Teton Village and Wilson areas (fig. 42, kilometer 29–42, mile 18–26), the maximum Pinedale fill terrace is only 3–5 m (10–15 ft) above the Snake River. On the west side of West Gros Ventre Butte in an old gravel pit just north of Wyoming Highway 22 (fig. 4), a pre-Pinedale landscape exhibiting Bull Lake glacial till with a strong soil mantled by loess only 7 m (20 ft) above the Snake River indicates that Pinedale flows were below this level. Thus, any Pinedale flows (Pd-1, 2, or 3) were lower than this level, and the Pd-3 floods would have readily covered this low terrace.

West of the Snake River, this low terrace also has channels of intermittent surface drainage oriented obliquely towards the Teton Range front at an angle up to 30° clockwise from the trend of the Snake River. Gravel-laden Pd-3 floods are likely to have formed these channels as they swept across this low terrace. A younger Pinedale age for this low terrace is indicated by a calcic soil profile with carbonate coats a millimeter thick and a thin to absent cover of loess.

Pinedale Glacial Troughs

Glacial excavation of troughs is an important aspect of the landscapes of Jackson Hole. Glaciers commonly excavate deep basins near their terminus. The method of excavation has been commonly considered to be scour at the base of glaciers including shear upslope as driven by the positive slope of the glacier surface. A more recently suggested process is erosion by confined and pressurized jets of water at the base of the glacier (Booth and Hallet, 1993; Stucki and others, 2010). The “head” for this confined hose-like flow is farther up the glacier, where the altitude of the water table in the glacier is above that of the discharge at the snout of the glacier. The gravel eskers noted at the head of the South Landing outwash fan (fig. 38) support the idea of subglacial erosion by a pressurized stream of confined water.

The unconsolidated basin fill of Jackson Hole as well as the Mesozoic and Paleogene sediments on the east side of Jackson Hole (Love and others, 1992) facilitated glacial excavation. The sand, silt, and clay of such excavations was mostly transported out of Jackson Hole, but the gravel required steeper stream gradients to be transported and was more readily deposited in Jackson Hole. In addition, the downward flexure of the crust by the weight of the GYGS (Anderson and others, 2014; Hampel and others, 2007) diminished the southward gradient of streams and also fostered gravel deposition.

The excavation of glacial troughs in Jackson Hole has led to societal impacts as well. For example, the possible liquefaction of unconsolidated fine sediment filling a trough 185 m (600 ft) deep beneath the Jackson Lake dam and dike prompted safety concerns that drove major mitigation projects deemed necessary to strengthen these structures (Gilbert and others, 1983). In addition, lakes in basins excavated by glaciers attract visitors.

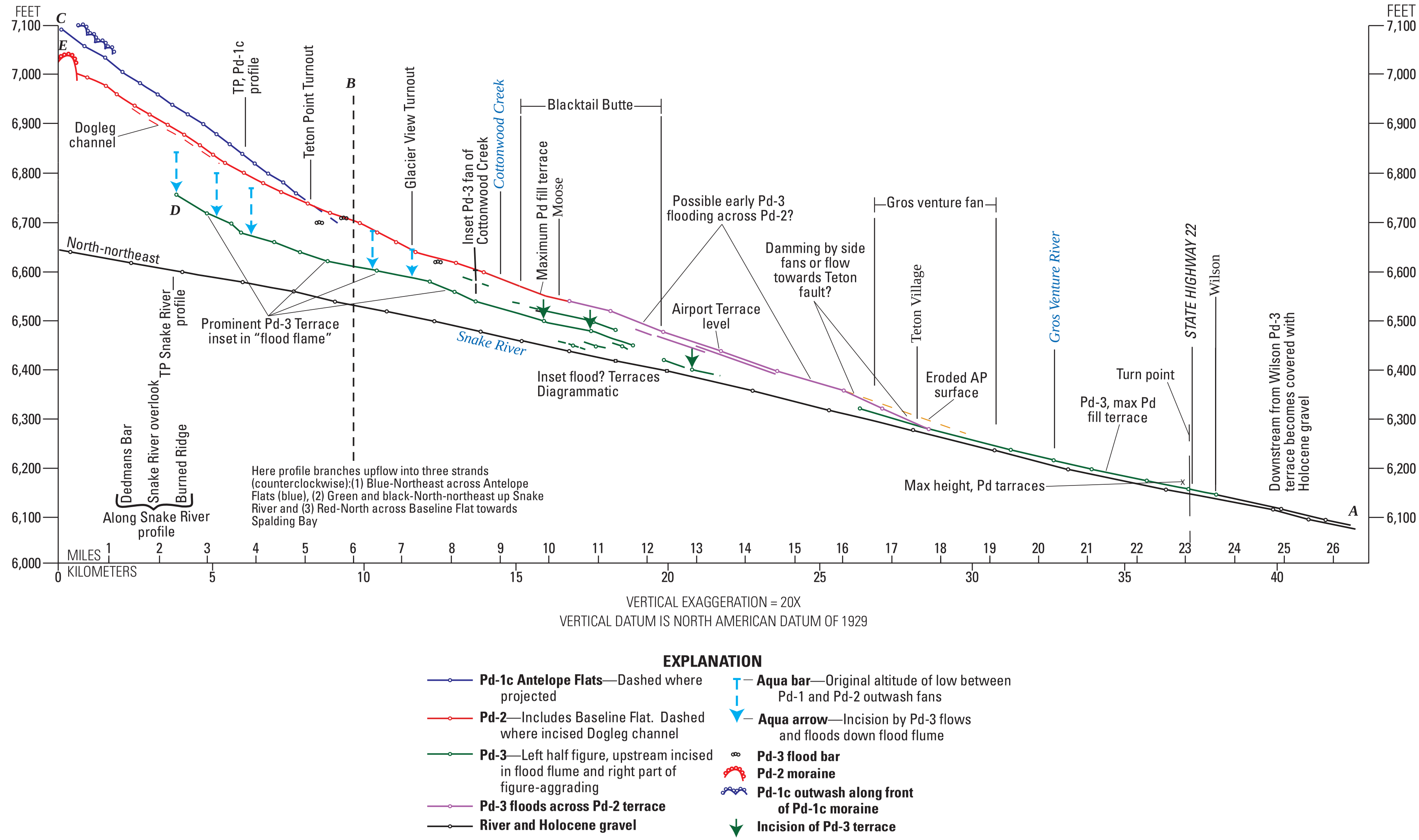

Figure 42. Longitudinal profiles of Pd-1, Pd-2, and Pd-3 terraces adjacent to the Snake River in Jackson Hole. The location of the terrace and river profiles is shown in figure 4. The Pd-1 terrace sloped to the west and southwest as shown in figure 22. The modern course of the Snake River became established in Pd-2 time by following the topographic lows of the Pacific Creek and Triangle-scour basins and then the topographically low seam between the Pd-1 and Pd-2 outwash fans. All the terraces converge downstream towards the present Snake River. A large volume of quartzite-rich gravel was readily carried to the glacial front and there the outwash stream had either to carry the gravel downstream or deposit it. The copious volume of quartzite cobbles combined with and glacio-isostatic back-tilting of the Snake River resulted in an unusually thick accumulation of gravel. The Pd-3 terrace levels headed in the Triangle-X-2 lake and had no gravel load other than what it eroded from the inset terrace. The terraces are difficult to separate downstream from Moose, but based on the shingling effect of terraces downstream (Pinedale Terrace Profiles and Outwash Relations), the highest fill terrace downstream from Teton Village is only 3 meters (10 feet) above the modern Snake River and is of Pd-3 age.

Compared to the Pinedale, the Bull Lake glaciation traversed a much larger expanse of the unconsolidated fill of Jackson Hole and seems likely to have excavated glacial troughs. Unfortunately, little is presently known of such troughs, but, as discussed at the end of the Bull Lake section, some evidence suggests buried lake sediments filling a possible trough in the area from Moose to the Jackson Hole Airport.

Pinedale-1 Troughs

Four Pinedale-1 (Pd-1) glacial troughs now form scenic bottomlands or lakes in northern Jackson Hole (fig. 21). These were basins formed by westerly to southwesterly flow of the Buffalo Fork and Pacific Creek lobes in Pd-1 time and are now largely filled with younger fine-grained lake and alluvial sediment.

Triangle X Trough

The Triangle X basin is a large trough more than 20 km (13 miles) long and ~6 km (4 miles) wide (fig. 21). Parts of the incompletely filled basin are reflected by the wide, flat, moist lowlands upstream from the Snake River Overlook to the Snake-Buffalo Fork confluence and from there up the Buffalo Fork for more than 10 km (6 miles). A test hole by the U.S. Army Corps of Engineers 0.9 km up the Buffalo Fork from its confluence with the Snake River penetrated lacustrine deposits(?) from 5 m to at least 16 m (16 feet to at least 52 feet) (McGreevy and Gordon, 1964). A cross section based on wells near the Snake-Buffalo Fork confluence encountered 6 m (20 ft) of alluvium on 25 m (80 ft) of lacustrine deposits resting on Cretaceous bedrock at a depth of 25 m (80 ft) below the present river level (McGreevy and Gordon, 1964, fig. 6). A well at the Moose Creek Ranch drilled to a depth of 10 m (30 ft) was in fine sediment inferred to be mostly lake sediment.

Two ages of Triangle X-1 lake sediments were deposited in this Pd-1 trough (fig. 21): Triangle X-1 sediments deposited between Pd-1 and Pd-2 time, and Triangle X-2 sediments deposited after retreat from the Pd-2 terminal position and into Pd-3 time. The abundant fine-grained component of the till shown in figure 25 facilitated the Pd-2 advance across the Triangle X-1 lake sediments. Exposures of Triangle X-2 lake sediments are recognized in the following places: (1) northwest bluff of the Snake River 0.5–2.5 km southwest of Moran Junction; (2) low bluffs on the southeast side of the Snake River 3.5 km southwest of Moran Junction; and (3) bluffs on the northwest side of Snake River 4–7 km northeast of Deadmans Bar with southeast-dipping cross beds.

Emma Matilda and Two Ocean Lakes

Emma Matilda and Two Ocean Lakes are remnants of Pd-1 scour basins (fig. 21) formed by westward flow of the Pacific Creek lobe. The presence of the Buffalo Fork lobe crowded the Pacific Creek lobe to this more westerly glacial flow direction. A two-sided kame gravel terrace now blocks the western part of both lake basins. These two-sided kame terraces slope to the south and were built by glacial outwash in recessional Pd-3 time, between the Pacific Creek lobe on the east sides and the Snake River lobe on their west sides. These two scour basins are now perhaps 10 km from the inferred Pd-1 terminus and a buried part of these basins may extend to the west.

Pacific Creek-Oxbows-Jackson Lake Dam-Donoho Trough

A deep fjord-like scour trough was excavated by the Pacific Creek lobe from lower Pacific Creek almost to Spalding Bay (fig. 21). This trough is documented in different parts of the landscape from east to west as follows: (1) for ~6 km up the valley of Pacific Creek where the valley bottom is 1 km wide and exploratory drilling found unconsolidated sediment to a depth of 60 m (200 ft), (2) from the mouth of Pacific Creek to beyond The Oxbow Bend area where westward glacial scour was opposite to the flow of the present Snake River and no bedrock is exposed in the valley bottoms that are wider than 1 km, (3) beneath the dike of the Jackson Lake dam where drilling encountered lake sediments to a depth of 180 m (600 ft) (Gilbert and others, 1983), and (4) between Donoho Point and Signal Mountain where Jackson Lake water depths are 40 m (125 ft) and sediment fill is >75 m (>250 ft) (Smith and others, 1993), for a total depth of scour below the present reservoir of >115 m (>375 ft).

Jackson Lake—Pd-2 and Pd-3 Glacial Trough

Jackson Lake was excavated in Pd-2 and Pd-3 time (figs. 24 and 34). The present dam and reservoir hold as much as 11 m (35 ft) of water above the natural lake level, which was about 15 km long, 5 km wide and locally 120 m (400 ft) deep. Beneath the deeper part of the lake, an inferred scour basin extends as much as 120 m (400 ft) deeper for a total depth of inferred scour of about 240 m (800 ft) (fig. 43; Smith and others, 1993, their fig. 9). The front of the Snake River delta built by the pre-dam lake slopes ~6°. Reflectors below the deeper part of the lake indicate sediment deformation (fig. 43). Several packets of deformed sediment are shown by the seismic records (fig. 43). These packets of deformed sediment may result from landsliding of the liquefaction-prone delta associated with large earthquakes on the Teton fault including the jolt (rebound) following downdropping of the basin.

Volumes of Jackson Lake Trough and Associated Outwash

Given the extent of the Jackson Lake scour basin and the large amount of outwash gravel in the associated outwash fans, we make a rough estimate of their volumes even though

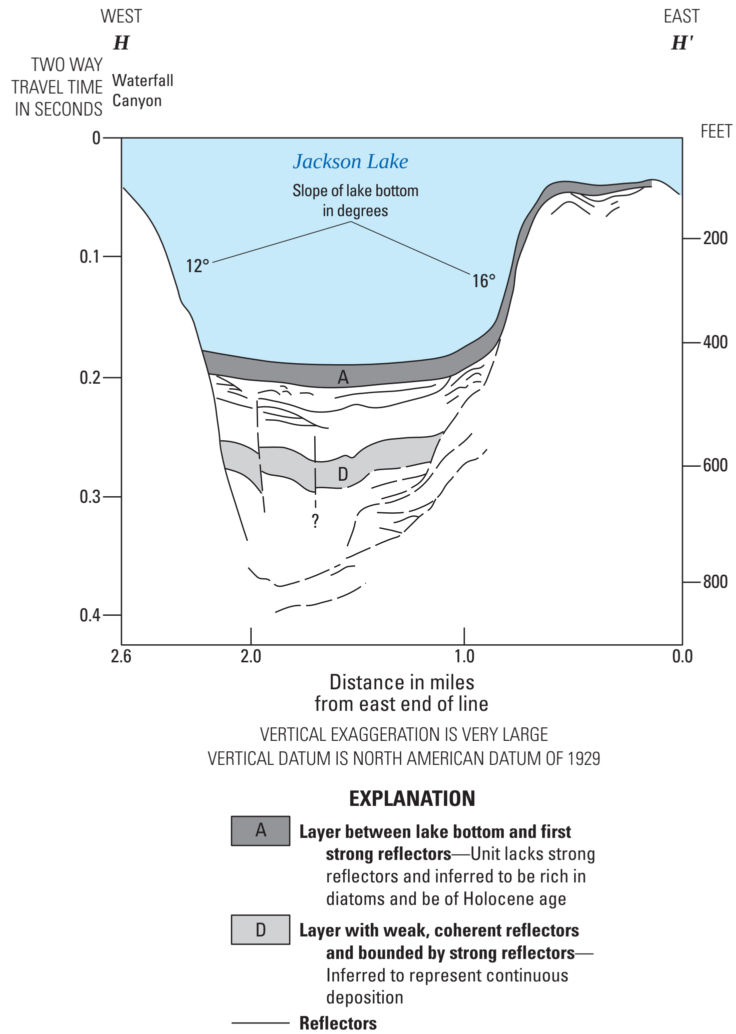

Figure 43. Jackson Lake located in Section *H–H'* of figure 4. Jackson Lake is about 120 meters (400 feet) deep here and below the lake bottom there are about 120 meters (400 feet) unconsolidated deformed material that may result by slumping of the post-glacial delta from the north end of the lake. Seismic cross section from Smith and others (1993c).

uncertainties are quite large. An estimate of the volume of sediment excavated from the Jackson Lake basin, including that now beneath the Snake River delta plain north to Lizard Creek, is roughly 6 cubic kilometers (km^3). This assumes an average width of 2.5 km, length of 20 km and depth of 0.12 km (120 m). At least some of this estimated volume would have been gravel, based on Pd-1 quartzite-rich gravel and till at reservoir level on Elk Island and east of Jackson Lake. This volume of 6 km^3 of glacially scoured and eroded sediment would have been discharged at the head of the outwash fans in Pd-2 and Pd-3 time.

For an estimate of the volume of Pd-2 outwash, we divide the outwash into two sectors. For the outwash fan north of Moose, an average length of 12 km, width of 6 km, and thickness of 0.03 km (30 m or 100 ft) yields a volume of 2.16 km^3. For the Pd-2 outwash downstream from Moose, an average length of 30 km, width of 5 km and thickness of 0.005 km (5 m or 15 ft) yields an additional volume of 0.75 km^3.

For the combined Pd-3 Potholes and South Landing outwash fans, a length of 4 km, width of 6 km, and thickness of 0.01 km (10 m or 30 ft) yields a volume of 0.24 km^3.

The total estimated volume of Pd-2 and Pd-3 gravelly outwash down glacier from Jackson Lake is roughly 3 km^3. Given that the estimated volume of the Jackson Lake scour basin is about twice this volume of combined Pd-2 and Pd-3 outwash, the excavation of the Jackson Lake scour basin was likely an important source for the Pd-2 and Pd-3 outwash in Jackson Hole. Glacial erosion from other sources was also significant and gravel deposition associated with glacio-isostatic northward tilting of the crust is also involved.

Conclusions

Pleistocene glaciations were a key factor in creating the spectacular landscapes of the Jackson Hole area. Extensive glaciation of the Greater Yellowstone glacial system (GYGS) occurred because of two processes related to the Yellowstone hotspot : (1) uplift of the Yellowstone Crescent of High Terrain (YCHT) that created the high, cold landscapes; and (2) the lowland track of the hotspot (eastern Snake River Plain) that provided, and still provides, a lowland conduit for moisture-laden storms from the Pacific Ocean to penetrate far inland and then to rise and produce deep orographic snows upon encountering the YCHT.

The Bull Lake (penultimate) glaciation filled all of Jackson Hole with ice and extended 48 kilometers (km) beyond the Pinedale glacial limit. This is the greatest separation of these two glacial extents in the Rocky Mountains. Boulders on the Bull Lake moraines date to 150 ± 4 ka and correlate with Marine Isotope Stage 6 (MIS 6). Although Bull Lake glacial features are more subdued than those for the Pinedale, glacial molding of East and West Gros Ventre buttes and deep ice marginal channels are clearly preserved. As much as 8 meters (m) of loess was deposited on Bull Lake outwash terraces and such loess deposition also subdued Bull Lake moraine expression.

Bull Lake glaciation was much more extensive than the Pinedale glaciation to the south, southwest, and west sides of the GYGS, but was much less so on the north and east sides. This geographic pattern in the relative extents of Bull Lake-Pinedale glacial limits may be explained by ongoing uplift on the leading margin of both of the YCHT and GYGS followed by subsidence on the trailing margin as the North American plate moved slowly to the southwest over the Yellowstone hotspot.

During the last or Pinedale (Pd) glaciation, valley glaciers formed in the Teton Range and deposited moraines along the west side of Jackson Hole, where lateral and end moraine boulders have exposure ages of ~21 to 14 ka. The local valley glaciers of the Teton Range sculpted U-shaped valleys, built moraines at the edge of Jackson Hole, and carved the high peaks into horns and serrated ridges. However, much larger Pinedale glaciers advanced into Jackson Hole along the southern margin of the GYGS. Three lobes fed into Jackson Hole: (1) the Buffalo Fork lobe from the east; (2) the Pacific Creek lobe from the northeast; and (3) the Snake River lobe from the north. The relative dominance of these lobes changed through time, migrating to the west as the icecap became established on the Yellowstone Plateau and then migrated to the southwest in the direction of moisture supply from storms moving eastward up the Snake River Plain.

Glacial outwash from these lobes is quite thick and readily defines three stages of the last glaciation: (1) Pd-1 outwash on Antelope Flats; (2) Pd-2 outwash forming a large fan heading south of Spalding Bay; and (3) Pd-3 outwash forming The Potholes, South -Landing and Cow Lake fans that were built into the Triangle X-2 lake basin. On its eastern margin, this Pd-2 outwash fan overlapped the lower part of the southwest-sloping Pd-1 fan creating a topographically low seam that became the present course of the Snake River.

In Pd-1 time, the Buffalo Fork lobe reached its maximum extent and was joined by the Pacific Creek lobe. Along the south side of the Buffalo Fork lobe, the ice-marginal Spread Creek spilled into the east side of Jackson Hole and deposited the Antelope Flats outwash. Three positions of Pd-1 ice (Pd-1a, 1b, 1c) occur over a distance of 3.3 km. The combined Buffalo Fork and Pacific Creek lobes carried Pinyon-type quartzite up the Snake River valley as far as Arizona Creek, where kame gravel benches suggest blockage of the Snake River valley. Thus, in Pd-1 time the Snake River lobe of the icecap on the Yellowstone Plateau was well north of Jackson Lake. The Pd-1 glacial culmination is considerably older than the Pd-2 stage of the Pinedale, and most likely dates to ~21–18 ka. The Pd-1c outwash slopes west at a gradient of about 12 meters per kilometer and projects beneath the Pd-2 outwash west of the Snake River. Pd-1 glaciers excavated deep scour basins in the following locations: (1) from the Snake River Overlook area to the Snake River-Buffalo Fork confluence and up Buffalo Fork for a total of more than 20 km; (2) from the Donoho Point area eastward beneath the Jackson Lake dam and Oxbow Bend and up Pacific Creek for a total of more than 15 km; and (3) the present locations of Two Ocean and Emma Matilda Lakes.

In Pd-2 time, the Snake River lobe and adjoining Teton ice built the type Pd-2 moraine south of Spalding Bay with large boulders that date 15.5 ± 0.5 ka. The Pd-2 outwash fan heads at this moraine and spans most of the area between the Teton Range and the Snake River. Farther east in Pd-2 time, the Snake River lobe was joined by the Pacific Creek lobe, slid across Triangle X-1 lake sediments, and deposited moraines, outwash gravels, and very muddy till that forms the Hedrick Pond bench. Farther northeast, Pd-2 moraines slope to the east on the Spread Creek hill. Thus, the combined Pacific Creek-Snake River lobes advanced eastward up the Buffalo Fork valley and into terrain occupied previously by the Pd-1 Buffalo Fork lobe. Between Pd-1 and Pd-2 time, the Buffalo Fork lobe had retreated more than 20 km whereas the Snake River lobe had advanced a similar amount. This is explained by the southwestward buildup of the icecap on the Yellowstone Plateau that generated the Snake River lobe and concurrently placed the Buffalo Fork lobe in a snow shadow.

Compared to the Pd-2 glacial position, the Pd-3 represents recession to a more stable position close to the margins of Jackson Lake. The largest change from Pd-2 to Pd-3 conditions was glacial recession from the Triangle X basin. Three large outwash fans including The Potholes, South Landing, and Cow Lake fans were built into this newly deglaciated area. Near the head of the South Landing fan, gravel eskers climb from the present-day level of Jackson Lake to the head of outwash, suggesting that confined subglacial streamflow was capable of eroding and transporting sediment at the base of the glacier.

The Jackson Lake scour basin was excavated in Pd-2 and Pd-3 time. Jackson Lake is approximately 120 m deep. Beneath the lake bottom there may be as much as 120 m more of deformed sediment filling this glacial trough which may result from landsliding of the Snake River delta associated with earthquakes. A rough estimate of the sediment excavated from the Jackson Lake basin is 6 km^3. The volume of Pd-2 and Pd-3 outwash fans is roughly 3 km^3 so glacial excavation of the Jackson Lake basin may have been a significant sediment source.

The extremely large amounts of gravel in the Pinedale glacial deposits result from two factors: (1) the abundance of poorly consolidated quartzite gravel in Cretaceous to Paleogene formations that glaciers could readily erode; and (2) glacial loading and depression of the lithosphere that reduced the gradient of south-flowing drainage of Jackson Hole. The sequence of Pinedale terraces has a shingle-like pattern with younger terraces burying older ones so that the highest Pinedale fill terrace becomes younger down valley.

Cosmogenic ^{10}Be surface exposure ages of Pinedale terminal moraines around the periphery of the GYGS are younger to the southwest reflecting buildup towards the source of moisture. This buildup and advance of the GYGS to the southwest also placed the eastern part of the GYGS in a precipitation shadow, resulting in concurrent glacial recession.

In conclusion, the complex glacial and tectonic history of the Jackson Hole area is fundamental to the dramatic landscapes we see there today.

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