# QUATERNARY AND LATE TERTIARY OF MONTANA: CLIMATE, GLACIATION, STRATIGRAPHY, AND VERTEBRATE FOSSILS

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## 1. INTRODUCTION

The landscape of Montana displays the Quaternary record of multiple glaciations in the mountainous areas, incursion of two continental ice sheets from the north and northeast, and stream incision in both the glaciated and unglaciated terrain. Both mountain and continental glaciers covered about one-third of the State during the last glaciation, between about 21 ka* and 14 ka. Ages of glacial advances into the State during the last glaciation are sparse, but suggest that the continental glacier in the eastern part of the State may have advanced earlier and retreated later than in western Montana.* The pre-last glacial Quaternary stratigraphy of the intermontane valleys is less well known. Mapping of deposits older than the last-glacial maximum (LGM) is spotty. At least four glacially dammed lakes existed across the central part of Montana.

Outside of the Flathead Valley, broad exposures of Tertiary (Paleogene and Neogene) sedimentary rocks at the surface, and shallow depths to them in wells in many valleys in western and central Montana, point to the Quaternary generally being a time of erosion rather than sedimentation in the intermontane valleys. In the Flathead Valley and northern Swan Valley, Quaternary sediments may extend to depths of 120 m (700 ft) or more below the surface in deep troughs of glacial and/or tectonic origin.

Flights of terraces along the major stream systems represent periods of stability and deposition followed by incision on timescales of <10 ka to ~2 Ma. Much of the response can be associated with Quaternary climate changes, whereas tectonic tilting and uplift may be locally significant.

The landscape of Montana is a result of mountain and continental glaciation, fluvial incision and stability, and hillslope retreat. The Quaternary geologic history, deposits, and landforms of Montana were dominated by glaciation in the mountains of western and central Montana and across the northern part of the central and eastern Plains (figs. 1, 2). Fundamental to the landscape were the valley glaciers and ice caps in the western mountains and Yellowstone, and the continental Laurentide and Cordilleran ice sheets that advanced southward into Montana Plains and western mountains, respectively (fig. 3). In intermontane valleys and along many of the major drainages in the Plains region, fluvial deposition and incision leading to terrace formation, and alluvial fan sedimentation and pediment formation, created areas of low relief that are now locations for human habitation, farming, and ranching.

Now classic studies of broad regions of Montana were carried out in the early to mid-20th century (Alden, 1932, 1953; Howard, 1958, 1960); many of their observations and conclusions are still relevant today. More recent overviews of the Quaternary geologic history of Montana have been limited to regional studies, such as in the Yellowstone area (Licciardi and Pierce, 2018; Pierce, 1979; Pierce and others, 2014b) and the eastern and central Plains (Wayne and others, 1991). The overall distribution of late Pleistocene glaciers in the mountains and/or Plains regions (Locke and Smith, 2004; Fullerton and others, 2004a) of North America were compiled in a volume on the extent and chronology of Quaternary glaciations (Ehlers and Gibbard, 2004).

*All radiocarbon ages are reported as cal ka BP or cal yr BP, depending on how they were originally published. Radiocarbon ages ($^{14}$C yr BP or $^{14}$C ka BP) were converted to calendar ages using the IntCal13 calibration curve (Reimer and others, 2013), with Calib 7.1 (for numerical 2-sigma ranges). Optical (optically stimulated luminescence) and $^{10}$Be (cosmogenic radiogenic nuclide exposure) ages are reported in ka with standard error. Approximate ages are reported in ka.


Figure 1. Glacial ice (white) was distributed from Canada into the northern third of Montana during the last glacial maximum at about 15–20 ka. Area of the State of Montana shown by dashed outline, Pleistocene lakes shown in light blue; from Blakey, https://deeptime-maps.com (Blakey, 2016).

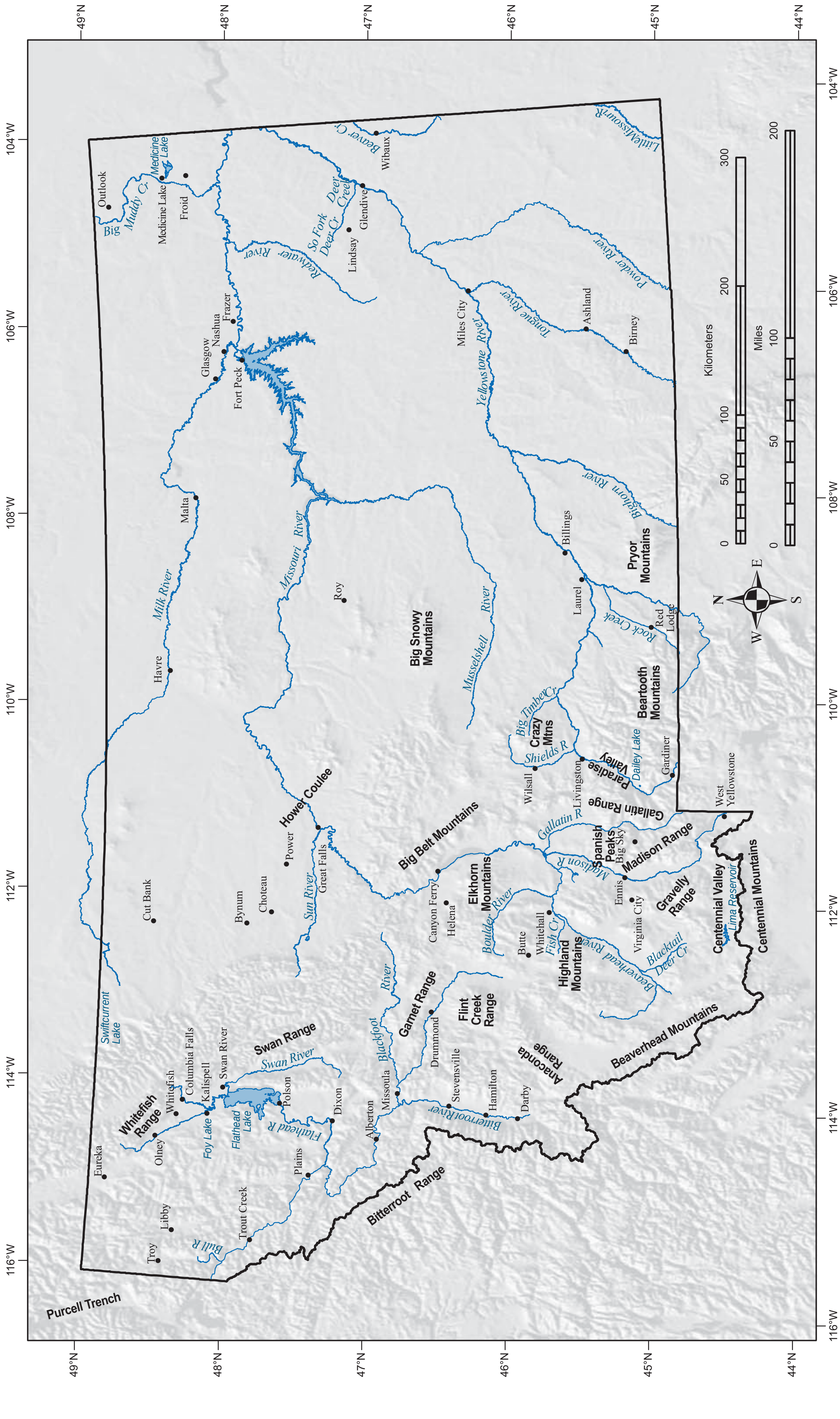



Figure 2. Locations mentioned in text.

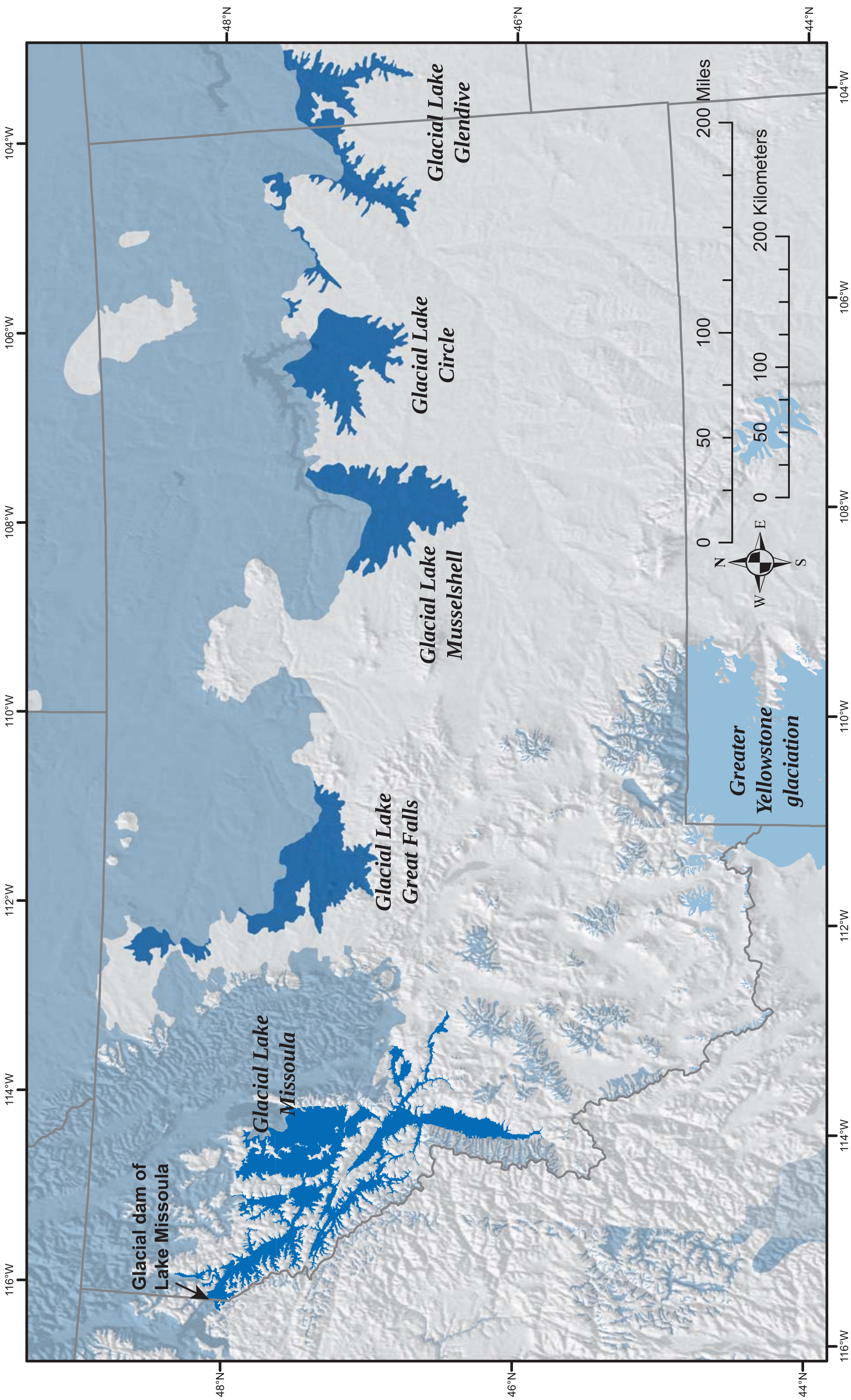



Figure 3. Distribution of last glacial maximum (LGM) glaciers in light blue; data from Ehlers and Gibbard (2004), but is incomplete in the mountains of Idaho; glacial lakes shown in dark blue.

The west-to-east division of topography, with mountains and the Continental Divide in the west, and the Plains in the east, has an impact on the State's climate. The climatic and paleoclimate regime of Montana were mostly affected by storm systems from the Pacific and Arctic oceans, generally moist and dry, respectively (Whitlock and others, 2017). The southeastern part of the State, including Yellowstone, are periodically influenced by moisture traveling northward from the subtropical Gulf of Mexico (Wuebbles and others, 2017) and the Snake River Plain (Licciardi and Pierce, 2018). Pleistocene glacial advance into Montana from the north and ice caps in the western part of the State affected the temperatures and storm tracks, as inferred from climate modeling and the distribution of mountain glaciers (Locke, 1990). Paleoclimatic studies in the mountainous regions and plains have been carried out by lake and wetland cores (Krause and others, 2015; Herring and Gavin, 2015; O'Neil and Stevens, 2015), inference from glacial and fluvial deposits (Locke, 1990; Pierce and others, 2014c), soils, dendrochronology (Gray and others, 2004; Pederson and others, 2006), fossil occurrences (Krause and others, 2015; Krause and Whitlock, 2017), and stable isotopes (Anderson and others, 2016).

Fossils of Pleistocene vertebrates have been recovered from a variety of stratigraphic and depositional contexts in Montana (Hill, 2006) and provide evidence of the changing patterns of biotic communities in this region of diverse and changing landscapes. The fossil remains have been found across Montana in both unglaciated and glaciated areas of the Montana Plains and the more extensive Rocky Mountains. Pleistocene faunas are found in a variety of depositional settings, including paludal-lacustrine and swamp-bog sediments, caves and rockshelters, alluvial deposits, fluvial terraces, debris flows, and uplands associated with eolian deposition and paleosols. The faunas can mostly be attributed to the Rancholabrean North American Land Mammal Age (NALMA), although there are some localities that can be assigned to the Irvingtonian and Blancan. Pleistocene mammals recovered from Montana represent taxa from Xenartha, Insectivora, Carnivora, Proboscidea, Perissodactyla, Artiodactyla, Rodentia, and Lagomorpha, as summarized in appendix A. The larger herbivores are fairly well represented. These include the ground sloths (*Megalonyx, Paramylodon*), proboscideans (*Mammuthus, Mammut*), horses (*Equus*), camelids (*Camelops*), cervids (*Odocoilheus*), antilocaprids (*Antilocapridae*), and bovids (*Bison, Bootherium/Symbos, Ovibos, Ovis*). Large to medium-size carnivores include the canids (*Canis, Vulpes*), felids (*Miracinonyx, Homotherium, Lynx*), mustelids (*Gulo, Mustela, Taxidea*), and bears (Ursidae undet., *Arctodus, Ursus*). Smaller mammals are also well represented and include the Sciuridae (*Cynomys, Marmota, Spermophilus, Tamiasciurus*), Castoridae (*Castor*), Geomyidae (*Thomomys*), Muridae (Arvicolinae: *Clethrionomys, Docrostonyx, Lemmiscis, Microtus, Phenacomys, Ondatra*; Sigmodontinae: *Neotoma, Peromyscus*), Erethizondtidae (*Erethizon*), and the lagomorphs (Ochontonidae: *Ochontonidae*; Leporidae: *Lepus, Sylvilgagus*).

Direct dating of the fossil remains provides chronologic controls on the landscape features and stratigraphic sequences where they have been discovered, and this in turn has provided a basis for developing models of Quaternary landscape evolution as well as examining the impacts of climate change on Quaternary ecosystems. The Quaternary mammals of Montana can be divided into two categories: those that are extinct and those that have survived from the Pleistocene (cf. Hill, 2006). Although many of the smaller mammals present in the Pleistocene still exist in the region, there have been shifts in some of their ranges. This is in contrast to the larger mammals; various taxa from the Pleistocene including some taxa of canids, felids, and herbivores have not survived from the Pleistocene.

The diverse topography and Quaternary process history of Montana leads to this review of the Quaternary history separated into physiographic regions, such as Alpine mountain areas, intermontane basins, and the eastern and central Montana Plains. The regional distinctions are not clear-cut because some of the alpine mountain areas fed distinct glacial deposits on the Montana Plains, and island mountains of central Montana are within the Plains region. Thus, for example, the Rocky Mountain Front area of northwestern Montana is included in the Plains. After a description of the overall physiography and character of the Quaternary in Montana, we provide a summary of paleoclimate studies. This is followed by a review of the Quaternary history of the different regions summarized in the context of glacial, lacustrine, eolian, alluvial, and hillslope processes and chronologies. We then offer some questions that could be pursued and avenues for future research.

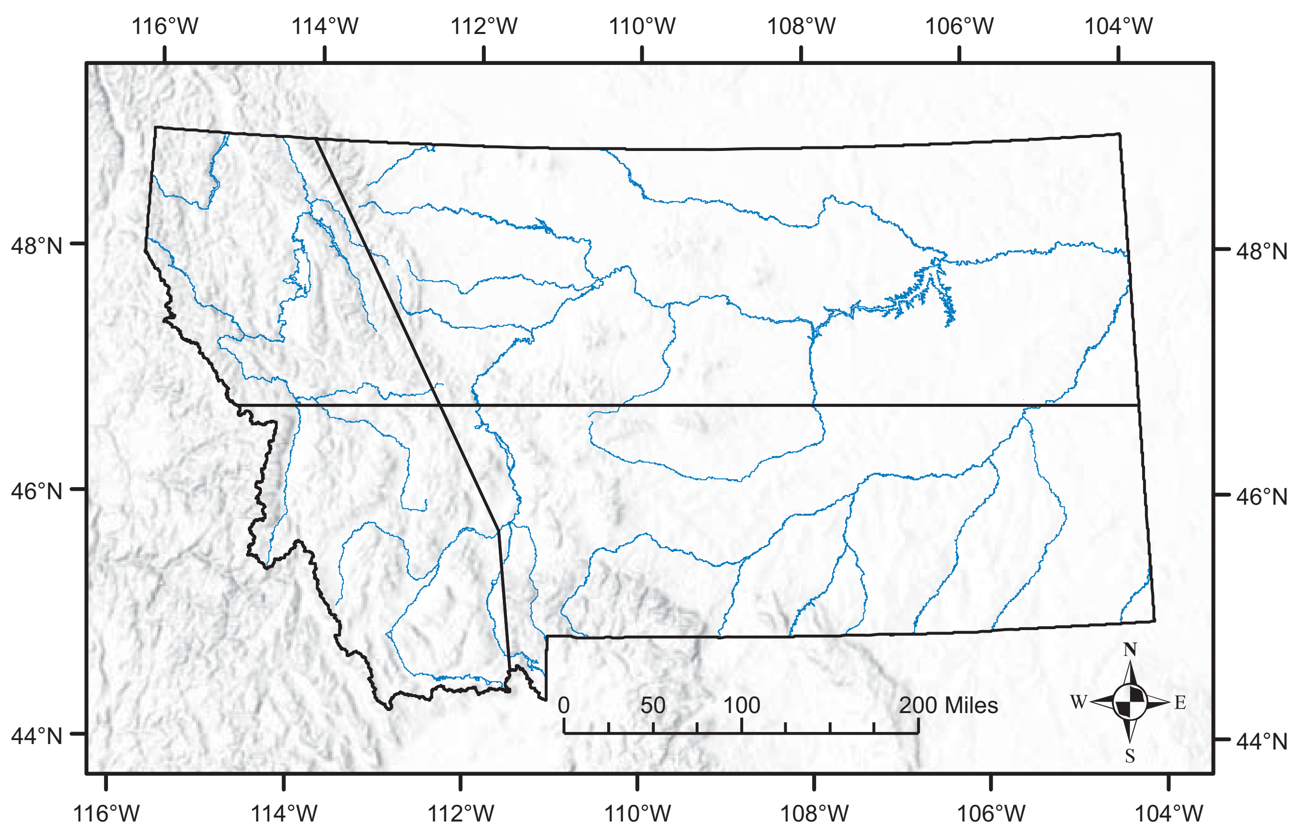
## 2. PHYSIOGRAPHY OF MONTANA AND DISTRIBUTION OF DEPOSITS

Montana is at the headwaters of three major drainages in North America. These are the Colombia and Missouri River Basins, to the west and east of the Continental Divide, respectively, and a small part of the northeast-flowing South Saskatchewan River Basin (fig. 4). About 35% of Montana is within the northern Rocky Mountain Province, and 65% is part of the Northern Great Plains. Most of the mountain ranges of western and central Montana are high enough to have supported valley glaciers during the Pleistocene (fig. 3). The land surface is composed of bedrock exposures in the mountainous regions, rolling hills with well- to poorly exposed bedrock, and valleys with vegetated alluvial and glacial deposits of Holocene and Pleistocene age. During the late Pleistocene glacial maximum, the Laurentide Ice Sheet, the Cordilleran Ice Sheet, or mountain glaciers covered about 34% of the State. Glaciation of the mountains of western Montana produced barren-rock alpine regions in many mountain ranges, stepped topography along mountain streams, boulder-strewn moraines (fig. 5), and alluvial outwash plains.

The landscape of the Plains of central and eastern Montana has evolved with Cretaceous, Tertiary, and Quaternary deposition and erosion. In the glaciated plains, several broad but highly dissected gravel-covered plateaus descend in altitude towards the south and east, where they were covered by low-relief, generally thin, glacial till. Glaciation by the Laurentide Ice Sheet brought sediment and boulder erratics southward from Canada, resulting in the less dissected, low-relief glaciated plains. The unglaciated central and southern parts of Montana are incised plains with thin soils. Nearly flat-lying bedrock with fluvial terraces along stream valleys and some areas with loess deposits with buried soils characterize these parts of Montana.

## 3. CLIMATE

Montana's size, its distribution of topography, and northern continental position cause the State's continental climate to range widely (Whitlock and others, 2017). The western part of the State has a modified




Sources: Esri, Airbus DS, USGS, NGA,NASA, CGIAR, N Robinson, NCEAS,NLS, OS, NMA, Geodatastyrelsen,Rijkswaterstaat, GSA, Geoland, FEMA,Intermap and the GIS user community

Figure 4. Physiography of Montana; the four physiographic divisions used in the chapter are shown. The easternmost portions of the Rocky Mountains are included in the Plains because glacial features extend east and produced stratigraphic units in central Montana.

Figure 5. The terminal moraine of the Flathead Lobe of the Cordilleran Ice Sheet is the hill across the lake in the foreground at Polson. The previously glaciated mountain topography of the Mission Mountains in the background contrasts the topographic expression of ice sheets and valley glaciers (reprinted from LaFave and others, 2004).

north Pacific coast climate, whereas the eastern part of the State is strongly continental with arid to semi-arid moisture regimes. The eastern three-fourths of the State has colder winters and warmer summers, higher winds, and generally higher humidity values than the western one-fourth. Average annual precipitation, modeled from 1,100 stations in Montana and 300 in adjacent areas, shows the strong control of topography and orographic precipitation-shadowing effects both in the mountainous regions and in broad areas of lower precipitation in the Plains (fig. 6; Farnes and others, 2011). In the western mountains, the western tracks of Pacific storms produce milder winters and more evenly distributed precipitation throughout the year than in the eastern Plains. Precipitation in the west is strongly affected by topography and orographic precipitation. Western-facing slopes receive more moisture than eastern-facing slopes, and some mountain slopes see 50–100 cm greater precipitation on the crests than at the base (fig. 6). The mean annual temperature, based on data from 1981–2010, was about 3.9°C in the western Montana mountains, whereas the eastern and central parts of the State showed approximately 6.7°C (Whitlock and others, 2017). Winters are cold, averaging -5.6°C across the State, and summer temperatures have mean daily highs above 32°C in the east and some of the lower western valleys (Whitlock and others, 2017).

## 4. QUATERNARY PALEOCLIMATE AND CHRONOLOGY

Climate transitions from glacial to interglacial times during the Quaternary produced advancing and retreating glaciers in the mountains and plains of Montana. Climate change also resulted in expansion and desiccation of inland lakes, mostly in the western intermontane basins. Glacial chronologies in the Northern Rocky Mountains were first based on inferred stratigraphic correlations of glacial and interglacial deposits with the use of relative weathering data and soil stratigraphy. Correlation of Quaternary events to the better time-constrained records of the western Cordilleran ice sheet and marine oxygen-isotope curve stages (MIS) leads to the conclusion that the younger record of glaciations and interglaciations in Montana is much better understood (Booth and others, 2003). Because erosion beneath advancing ice sheets and mountain glaciers makes the preservation of datable contemporaneous proglacial deposits unlikely, the stratigraphic record of ice advance is known

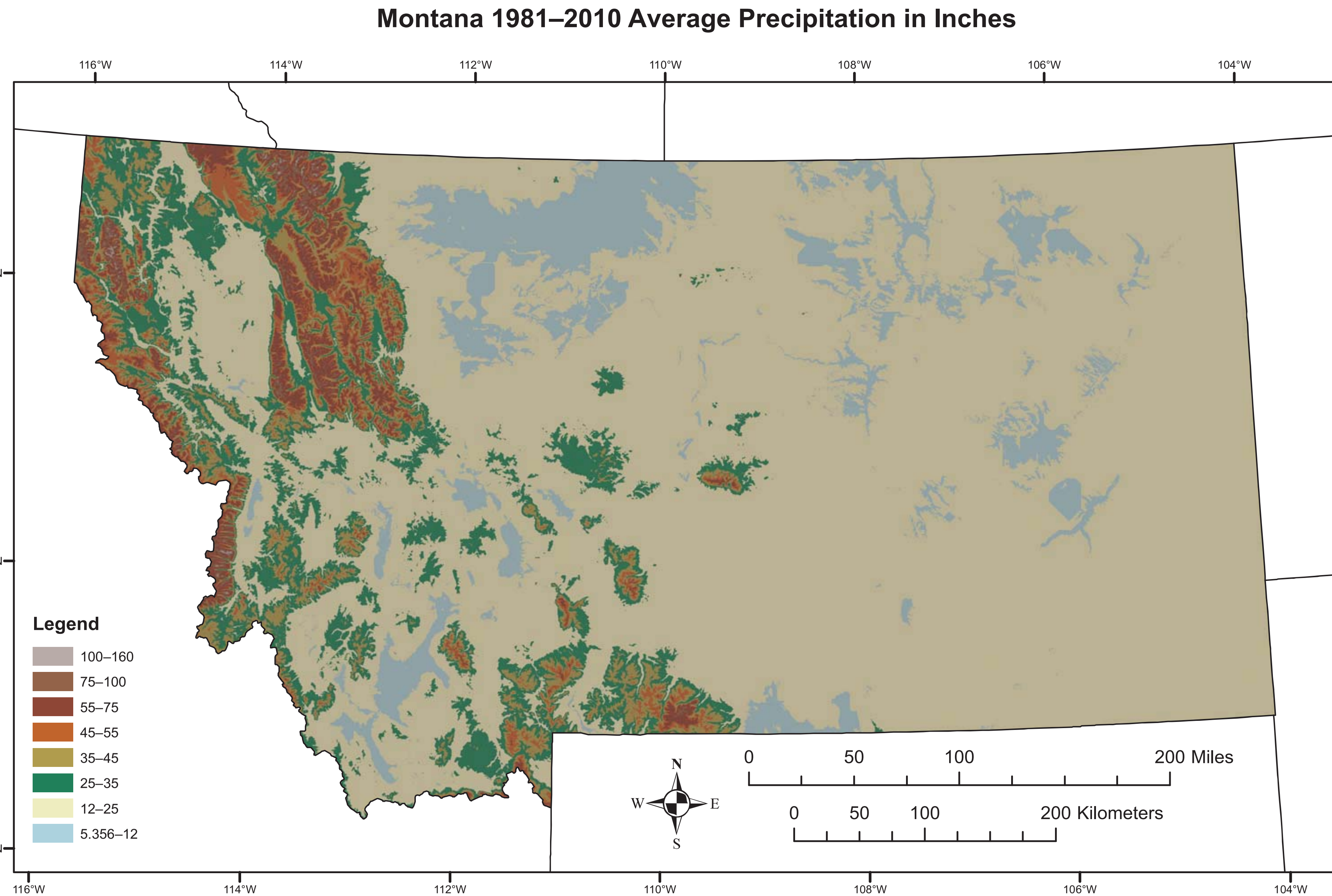



Figure 6. Average annual precipitation in mountains and valleys show significant orographic gradients and precipitation shadows; based on climate records from 1981–2010 water years (Farnes and others, 2011).

from a few limited areas (fig. 7A). Rare finds of organic material and fossils above and below glacial deposits allowed for radiocarbon ages that improved knowledge of (mainly) deglaciation (Carrara, 1995; Carrara and others, 1996). The advent of cosmogenic isotope techniques applied to boulders and soil profiles since the early 1990s has increased numerical ages in the literature, such as in Licciardi and Pierce (2018). Proxy records for Quaternary paleoclimates included glacier distributions for the Pleistocene and lake sediments and tree ring records for the Pleistocene–Holocene transition and Holocene climatic variations, as discussed below.

The effects of the positions of ice sheets and the Rocky Mountain ice cap to the north and the smaller ice caps in western Montana and Yellowstone were to steer westerly storm tracks southward of the ice sheets (Locke, 1990, 1995; Meyer and others, 2004; Thackray, 2008). Data collected over the broad region of the western USA show that the areas near the ice sheets,

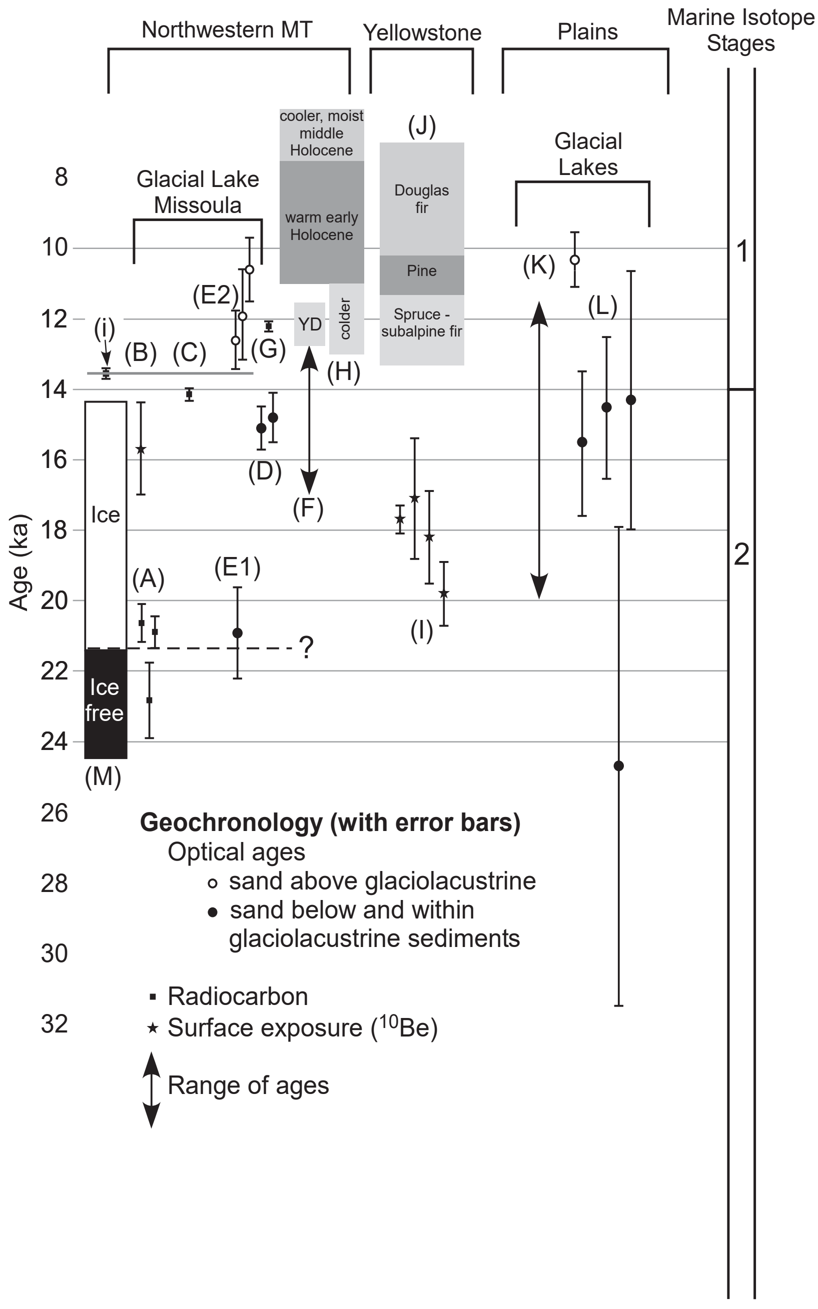



Figure 7A. Summary of a selection of relevant geochronologic data for MIS 1 and 2 last glacial (LGM), alluvial, and lacustrine deposits highlight the precision of data in Montana. Pleistocene and earliest Holocene deposits are shown, although details of the Holocene climate in Montana are difficult to generalize on a diagram. Advance and retreat of the Cordilleran Ice Sheet, shown by black and white bars (modified from Baker and others, 2016). (i) Age of the Glacier Peak "G" tephra (Kuehn and others, 2009) is shown by the horizontal gray line; it represents the minimum age for glacial Lake Missoula. (A) Times of glaciation Cordilleran Ice Sheet; the oldest calibrated $^{14}$C age indicates ice-free conditions in southeastern British Columbia (after Clague and others, 1980); the younger two calibrated $^{14}$C ages suggest active glaciers in southern British Columbia; the surface exposure age corresponds to the age for beginning retreat of the Purcell lobe at the ice dam (Breckenridge and Phillips, 2010, recalculated by Balbas and others, 2017). (C) Age of a pine needle in the upper part of a glaciolacustrine section of Flathead Lake core (fig. 1; Hofmann and Hendrix, 2010). (D) Two ages from the Glacial Lake Missoula deposits in the Missoula Valley (Hanson and others, 2012); see text for discussion. (E1) Weighted average age (*n* = 11) of glaciolacustrine sediments near Drummond and (E2) three ages of post-lake sediments (Smith and others, 2018). (F) The Grinnell Glacier as recorded at Swiftcurrent Lake shows glacial retreat beginning about 17 ka interrupted by an advance during the Younger Dryas from 12.75 to 11.5 ka (Schachtman and others, 2015). (G) Deglaciation of Marias Pass occurred by this time (Carrara, 1995). (H) A 13,100 yr record from Foy Lake, Montana and other lakes in the northern Rockies provide a climatic signature (Power and others, 2011). (I) Ages of the maximum extents of selected terminal moraines of the greater Yellowstone Glacial System from west (north of West Yellowstone) to east (south of Red Lodge), left to right respectively (Licciardi and Pierce, 2018). (J) Post-glacial climates are shown by changes in forest species in the Greater Yellowstone Ecosystem (Krause and Whitlock, 2017). (K) Seventeen $^{10}$Be ages on ice-rafted boulders in Glacial Lake Musselshell range from 20 to 11.5 ka (Davis and others, 2006). (L) OSL ages within and above Glacial Lake Great Falls sediments show the lake deposits are related to the last glaciation, during MIS 2 (Feathers and Hill, 2003, as modified by Hill and Feathers, 2019; see text for discussion); Marine Isotope Stage (MIS) boundary from Cohen and Gibbard (2016). (M) Inferred time of the onset and duration of the last glaciation in northwestern Montana, as compiled from available data summarized here.

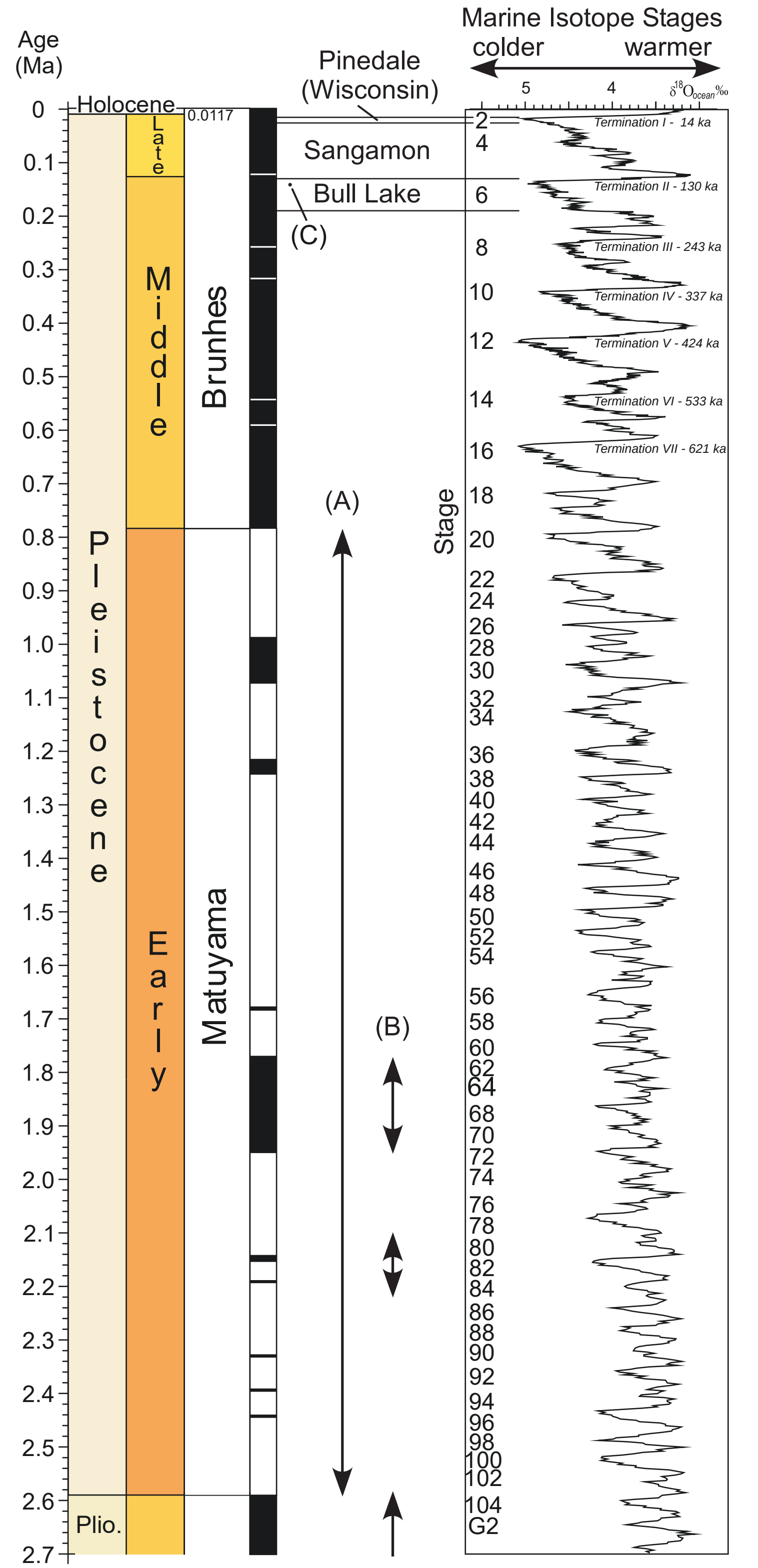



Figure 7B. Summary of Quaternary stratigraphy of pre-MIS 2 glacial deposits in Montana. The geomagnetic polarity time scale is shown with black as normal polarity and white as reversed polarity. (A) Eight different tills and paleosols at Mokowan Butte, Saint Mary Ridge, and Two Medicine Ridge near the Canada–USA border have reversed polarity and are correlated to the Matuyama Chron (Cioppa and others, 1995; Karlstrom, 2000). (B) Two diamictons (tills) with normal polarity underlie two with reversed polarity and are correlated with either the Gauss Chron (3.6–2.6 Ma) or possibly the Reunion or Olduvai events (2.23–2.2 and 1.93–1.76 Ma, respectively). (C) The Bull Lake glaciation near West Yellowstone Montana was dated by combined K-Ar and obsidian hydration as late MIS 6 (~140 ka; Pierce and others, 1976).

like Montana, were colder and perhaps drier relative to the current conditions (Oster and others, 2015).

### 4.1 Lake Cores

Studies of lake-sediment accumulation provide data on late Pleistocene and Holocene local climates through interpretation of plant taxa distribution. Because sites are areally restricted, individual lake records are representative of given elevations, aspects, and latitudes. At Slough Creek Lake in northern Yellowstone Park (Krause and others, 2015), upstream of the Yellowstone River at Gardiner, Montana and Dailey Lake, vegetation histories for the last 16 cal ka BP showed tundra vegetation expanded after deglaciation and that the climate was cooler and drier than present. Alpine landscapes in Glacier National Park provide a record of Younger Dryas cooling, from 12.75 to 11.5 ka, and warming into the Holocene (Schachtman and others, 2015). The vegetation transitioned to pine-juniper between 11 and 7 ka, during a climate that was warmer and wetter in the northern Yellowstone, and drier in the lower elevation valley at Dailey Lake (Krause and others, 2015; Krause and Whitlock, 2017). Fire frequency increased from the early Holocene to about 7 ka. A cooler and drier climate in the late Holocene resulted in increased fire activity in a Douglas Fir forest (Krause and others, 2015; Pierce and others, 2014c). Lower elevation sites like Dailey Lake in the Paradise Valley, and Foy Lake northwest of Flathead Lake, provide detailed records of early Holocene (Power and others, 2011) and mid- to late-Holocene (Stone and Fritz, 2006) postglacial fire activity, vegetation changes, and droughts (O'Neil and Stevens, 2015). Vegetation changes at higher and lower altitudes reflect how differing forest structures affect fire regimes and make for complex signals in lake records (Power and others, 2011).

Paleoclimatic records in the Plains have been obtained from shallow lake beds that have periodically desiccated. The diatom and carbonate stratigraphic sequence from Kettle Lake, North Dakota, provided a detailed record of arid and humid wet periods during the past 8,500 cal yr BP (Hobbs and others, 2011). This record indicates several humid/wet periods occurred between about 8,350–8,100, 4360–1400, and 872–620 cal yr BP, with more arid periods between those intervals.

### 4.2 Tree Ring and Other Climate Data

Tree ring records of climate have been used to extend instrumental records of summer and winter precipitation back about 500 yr in Glacier National Park and extending north of the Montana–Canada border with the goals of understanding climate variability and surface-water supplies (Sauchyn and others, 2003; Pederson and others, 2006; Axelson and others, 2009; Bonsal and others, 2017). Many of these studies put recent droughts along the northern tier of Montana into a millennial perspective. Along the Montana–Wyoming border, tree ring chronologies showed that instrumental records do not capture the wide range of precipitation variability (Gray and others, 2004). Millennial-scale records of vegetation derived from *Neotoma* (pack rat or woodrat) middens at low elevations in the northern Bighorn Basin show that the early Holocene was cooler than present and that later warming was interrupted by a wetter mid-Holocene, followed by increasing aridity (Lyford and others, 2002; Thompson and Anderson, 2000).

## 5. WESTERN MOUNTAINS, ALPINE AREAS, AND INTERMONTANE BASINS

### 5.1 Northwest

*5.1.1 Overview*

The northwestern part of the State refers to those areas between the Rocky Mountain Front on the east, and the Montana–Idaho border on the west, within the northern part of the Clark Fork River Basin (fig. 4). The Quaternary record in northwestern Montana is characterized by thin deposits of alluvium (mostly <20 m thick) along intermontane valleys (e.g., Smith, 2009) that extend towards mountain piedmonts, and tributary valleys with lateral and terminal moraines of valley glaciers, with the significant exception of the Flathead and Mission Valleys (LaFave and others, 2004). Several terraces along the axial and tributary streams are common. Most of the valleys contain incised terraces or “benches” that slope toward valley axes, some of which correlate with glacial deposits, such as in the Deer Lodge and Bitterroot Valleys (Weber, 1972; Berg, 2004).

*5.1.2 Glacial Deposits and Landforms*

Advance of the Cordilleran Ice Sheet into Montana occurred in multiple lobes along north–south-trending valleys. The most prominent of these is the Flathead Lobe in the Rocky Mountain Trench and Flathead Valley. Glaciation in western Montana involved advance of the Cordilleran Ice Sheet from the north as well as initiation and expansion of valley glaciers in most of the mountain ranges. Glacial advance of the Cordilleran ice during the LGM, between about 21 and 14 ka (fig. 7A), produced six distinct southern lobes in the northwestern USA. From east to west, these were: the Flathead Lobe near Flathead Lake; Purcell Trench Lobe near Lake Pend Oreille; Columbia River and Okanagan Lobes of central Washington; and Puget and Juan de Fuca Lobes of western Washington (Booth and others, 2003). The timing of glacial lobe advance into, and retreat from, Montana is not well known, but available data suggest that retreat of the lobes on the west occurred earlier than those to the east (Gombiner, 2019). The Flathead Lobe occurred in Montana, but the Purcell Trench Lobe in Idaho is important because it periodically dammed the Clark Fork River, forming Glacial Lake Missoula (fig. 8).

The Northern Rocky Mountain ice cap, centered in the mountains west of the Rocky Mountain Front and north of the present Blackfoot River, likely advanced at about the same time, eventually merging to form a continuous ice surface. Resulting LGM landforms include impressive drumlin fields near Eureka, Whitefish, and Kalispell; numerous ice-marginal channels cut into ridges of the Whitefish, Swan, and Mission Ranges; and terminal moraines at Polson (figs. 3, 5, 8), in Glacier National Park, near Libby, Troy, and near the confluence of the Bull and Clark Fork Rivers (Alden, 1953; Konizeski and others, 1968; Clague and others, 1980; Breckenridge and others, 1989; Smith, 2004).

Early investigations of the Quaternary history of northwestern Montana and surrounding areas documented multiple diamictons interbedded with fluvial or lacustrine sediment in the Flathead River Basin, downstream of Flathead Lake (Davis, 1920; Alden, 1953; Richmond, 1986). The diamictons were inferred to be till and the stratigraphy was interpreted to represent multiple periods of glaciation, as was documented across Europe and North America in the 20th century (Alden, 1953; Davis, 1920; Richmond, 1986). Further work in the Flathead River Basin showed that deposits and landforms ascribed to pre-LGM glacial advances were either Paleogene debris flows (Ryan and others, 1998; P. Ryan, Middlebury College, written commun., 2003, 2018), or sedimentation in Glacial Lake Missoula (Ostenaa and others, 1995; Levish, 1997).

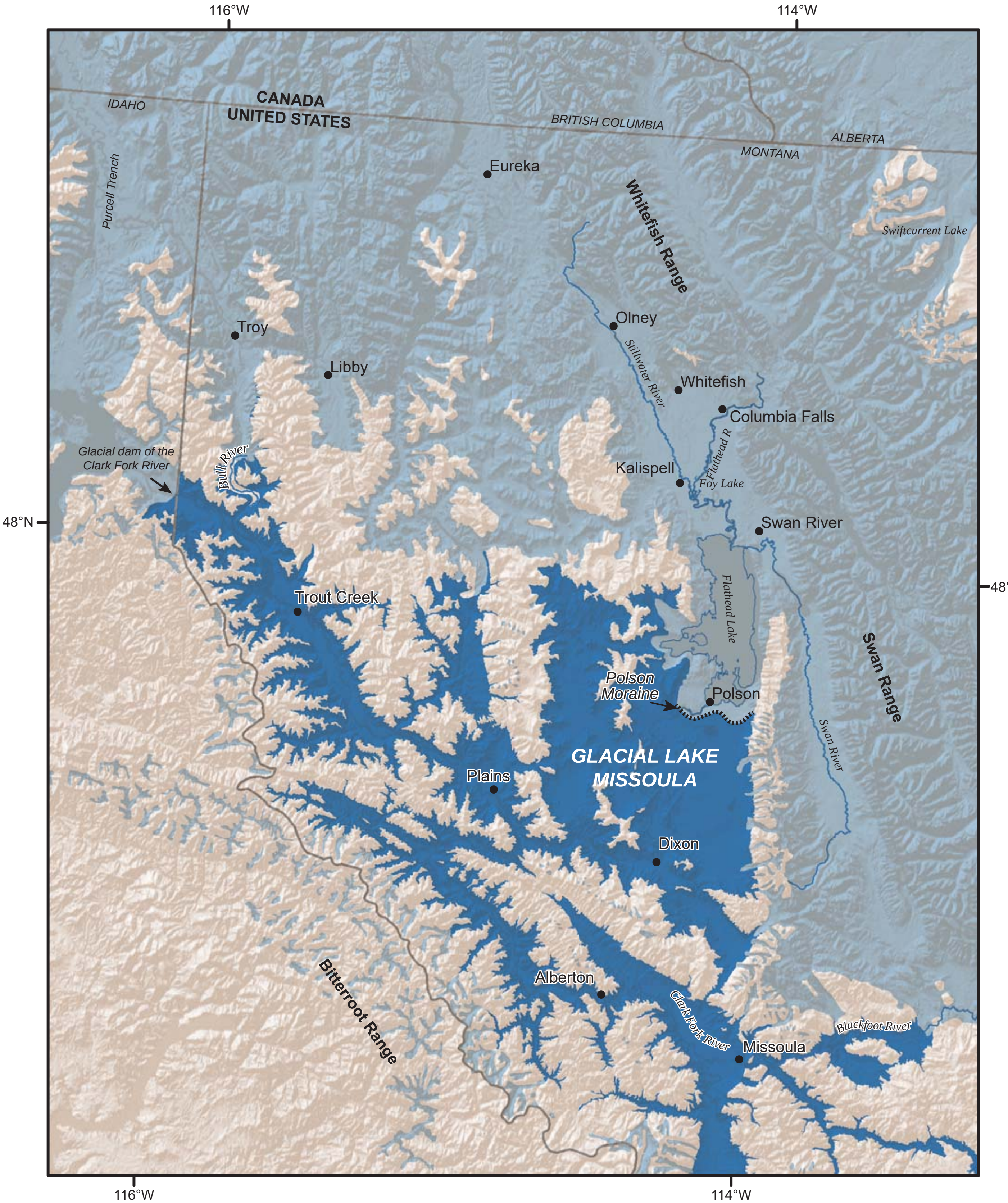



Figure 8. Northwestern Montana glaciers, glacial lakes, and glacial features.

Water-well drilling logs in the Flathead Valley encountered buried deposits interpreted as pre-LGM tills (LaFave and others, 2004; Smith, 2004), and till and ice-polished bedrock extends south of the Polson Moraine (fig. 2). Glaciation prior to the LGM apparently occurred in the valley, but its extent is unknown.

The best records of pre-Bull Lake (pre-MIS 6) glaciations in the Rocky Mountains are on terraces on the eastern slope of the Northern Rockies, near the Canada–USA border (fig. 7B) (Cioppa and others, 1995; Karlstrom, 2000; Pierce, 2003). Our current knowledge of Montana's glacial record is incomplete; the LGM is well represented by the recent extents of mountain, piedmont, and continental glaciers, whereas earlier glaciations have been documented only locally (Alden, 1953; Clague and others, 1980; Clague and Ward, 2011; Hanson and others, 2015; Karlstrom, 2000; Licciardi and Pierce, 2018; Locke and Smith, 2004; Pierce, 1979, 2003; Pierce and others, 2014b; Porter and others, 1983; Weber and Witkind, 1979). As in many glaciated regions, deposits of the advancing LGM glaciers are not well exposed, but deposits related to deglaciation are well expressed.

Work in central Washington on the timing of the ice advance and retreat and the establishment of Glacial Lake Missoula and other floods provides minimum ages for the maximum extent of the Purcell Trench Lobe (Balbas and others, 2017). The glacial advance into northwestern Montana and northern Idaho during and prior to the LGM is poorly constrained temporally. The retreat of the Purcell Trench Lobe from its most recent maximum position near Lake Pend Oreille has been carried out by $^{10}$Be exposure ages of a prominent moraine (Breckenridge and Phillips, 2010; Balbas and others, 2017) and radiocarbon ages along its path of retreat (Carrara and others, 1996; fig. 7). Timing of initiation and the last record of glacial Lake Missoula constrain when the ice dam was intact (fig. 7; Smith and others, 2018).

Drumlins formed during active glacial movement are cut across by younger scours as ice movement shifted in direction, and are draped by ablation till let down during wasting stages (Smith, 2004). Timing of the last glacial advance and retreat of the western Puget Sound lobe of the Cordilleran Ice Sheet is better known than that of the Purcell Trench or Flathead Lobes (Porter and others, 1983). However, available data suggest that the timing of advance and retreat of the Puget Sound, Purcell Trench, and Flathead Lobes was not necessarily synchronous, which complicates matters (Balbas and others, 2017). A few well-preserved eskers in the valley and subtle recessional moraines near Kalispell and Whitefish developed during minor readvances and regional retreat. Timing of deglaciation in alpine areas near Marias Pass was dated by a radiocarbon age and two tephras as prior to 14.8–13.7 cal ka BP (12,194 ± 145 $^{14}$C yr BP; Carrara, 1995), indicating that glaciers had retreated in the upper parts of the mountains, if not the lower regions, by then. It has been proposed that the Cordilleran Ice Sheet disintegrated in <1,000 yr after about 13 ka and was accompanied by significant release of meltwater and sediment (Eyles and others, 2018).

The distribution of the Glacier Peak "G" tephra shows that deglaciation of much of the alpine glaciers in Montana occurred prior to the Younger Dryas cooling episode that was associated with a significant glacial advance in Europe, but minor expansion of cirque glaciers in Montana (Schachtman and others, 2015) and elsewhere in the Rocky Mountains (Pierce, 2003).

Outwash containing outsized boulders, gravel, and sand and post-glacial alluvium were deposited across glacial lake sediments and till in the valleys (Konizeski and others, 1968; LaFave and others, 2004). The sizes of some of the boulders suggest that they were carried by floating ice (fig. 9). Most of the alluvium is confined to the present valleys of the Flathead, Stillwater, Whitefish, and Swan Rivers, suggesting that the courses of the rivers formed and downcut early during deglaciation and retreat of Glacial Lake Flathead.

*5.1.3 Glacial Lakes*

Three major glacial lakes formed in northwestern Montana during glacial advance and upon partial retreat. These three are: (1) Glacial Lake Missoula, formed by damming of the Clark Fork River by the Purcell Lobe of the Cordilleran Ice Sheet near its maximum position at Pend Oreille (Pardee, 1910; Breckenridge and others, 1989); (2) an early stage of Flathead Lake (Alden, 1953), later named Glacial Lake Flathead, formed behind its terminal moraine at Polson; and (3) Glacial Lake Kootenai, formed later as the Purcell Lobe dammed the recently deglaciated Kootenai River drainage in northernmost Montana (Alden, 1953).

Glacial Lake Missoula has received the greatest amount of attention. This is because of its well-expressed shorelines in the Missoula and Bitterroot

Figure 9. Glacial outwash deposits in the Flathead Valley contain outsized boulders that were carried into the valley as clasts suspended by floating ice; the Jacob's staff is 1.5 m (5 ft) long.

Valleys (Pardee, 1910; Weber, 1972), its great volume and area (as much as 2,500 km$^3$ of water across 11,000 km$^2$), and the effects of repeated dam failures causing rapid discharges (Pardee, 1942). Glacial Lake Missoula's multiple expansion and catastrophic drainage events are significant and unusual in the examples of glacially dammed lakes worldwide (Waitt, 1980, 1985; Baker, 2007). Glacial Lake Missoula extended from near the ice dam along the Clark Fork River, upstream to the terminus of the Flathead Lobe in the Mission Valley, to near Gold Creek along the Clark Fork River, and south to near Darby in the Bitterroot Valley (figs. 2, 3). Mount Jumbo, northeast of Missoula, has a good record of lake shorelines that range in altitude from about 1,050 to 1,297 m (3,450 to 4,255 ft) on the hillside; however, 1,280 m (4,200 ft) is generally considered the maximum pool height. Because isostatic adjustments have not been accounted for, absolute heights of the maximum water surface are not precisely known. Evidence for various ice dam positions along the Clark Fork River, mostly based on upstream-oriented fan delta deposits, shows that the glacier that dammed Glacial Lake Missoula extended at different times from west of the Montana–Idaho state line to near the present community of Trout Creek, Montana (Breckenridge and others, 1989; Smyers and Breckenridge, 2003).

Glacial Lake Missoula deposits along the Clark Fork and Flathead Rivers include laminated silty and clayey lake-bottom glaciolacustrine sediments and underlying gravel deposits along some valley bottoms, as giant bars, and as eddy deposits in side canyons (Pardee, 1910, 1942; Alt and Chambers, 1970; Chambers, 1971, 1984; Breckenridge and others, 1989; Alt, 2001; Smith, 2006, 2017; Lonn and others, 2007). Because of the lack of fossils, charcoal, and tephra within the lacustrine deposits, age control on and correlation of the deposits have required optical luminescence dating methods. Optical dating relies on luminescence characteristics of quartz and feldspar grains, which can be used to estimate the last time sediments have been exposed to sunlight (Roberts and Lian, 2015).

Optical dating has shown that initial formation of Glacial Lake Missoula during the LGM was apparently at about 20 ka (Smith and others, 2018). Hanson and others (2012) determined that the laminated glaciolacustrine sediment in the Missoula Valley was deposited after about 15.1 ± 0.6 ka. Multiple events of rapid lake-level lowering formed giant gravel bars along the Clark Fork River downstream from Missoula, and smaller, high-level eddy bars along the Flathead River. The deposits along the Flathead River are smaller than along the upper Clark Fork, because higher discharges on the Flathead prevented sediment from being preserved in mid-valley locations. These high-velocity drawdown events occurred earlier in the history of the LGM Glacial Lake Missoula, as they formed deposits that are overlain by silty and clayey glaciolacustrine beds. The gravel deposits represent earlier, high-discharge drawdown events, whereas glaciolacustrine sediments in valley-bottom positions record later, likely shallower lake stands (Smith, 2006). Preservation of the easily eroded sediments in valleys indicates that the later lake stands must have emptied with less erosional force than the earlier stands (Pardee, 1910, 1942). These later lake stands may be represented by the Missoula Valley ages of post 15.1 ± 0.6 ka (Hanson and others, 2012). The lake had drained for the last time before deposition of the Glacier Peak "G" tephra (Levish, 1997; Hofmann and Hendrix, 2010) at 13.6–13.3 cal ka BP (Kuehn and others, 2009; fig. 7A).

Glacial Lake Flathead is represented by shorelines along and north of Flathead Lake, lake-bottom lacustrine silt and clay in the Flathead Valley as far north as Olney, and a series of sublacustrine outwash fans that represent minor readvances of the Flathead Lobe. Stratigraphically above till in the Flathead Valley are rhythmically laminated glaciolacustrine sediments of the proglacial Lake Flathead (Konizeski and others, 1968; Hofmann and Hendrix, 2010), subglacial lake deposits that formed in erosional troughs below the ice (Smith, 2004), or possibly northeastern deposits of Glacial Lake Missoula that extended across Polson into the Big Arm of Flathead Lake. Till overlain by glaciolacustrine silt and clay forms a nearly continuous blanket over alluvium in the Flathead Valley, confining the extremely productive deep aquifer in the valley (see LaFave and others, 2004, vol. 2). During glacial retreat from what is now Flathead Lake, the Flathead River cut into the southwestern part of the Polson Moraine.

The sedimentology of the Kalispell moraine of Alden (1953) and others in the center part of the valley shows that it is mostly made up of water-laid sand and gravel that dispersed from esker or tunnel-channel outlets into a proglacial lake (Smith, 2004). The lake's shorelines show stands from altitudes of 975–930 m. The highest lake stands were impounded by till, which was likely rapidly downcut by the Flathead River until the river reached Belt Supergroup bedrock near Seli'š Ksanka Qlispe' (formerly Kerr Dam) at about 950–955 m (3,115–3,135 ft). Glacial Lake Flathead formed behind this bedrock ledge, and as the Flathead glacier ablated, the lake expanded northward to near the foothills of the Whitefish Range (Alden, 1953; Konizeski and others, 1968; LaFave and others, 2004; Smith, 2004). Over time, the dam downcut and the lake regressed until the dam was built in the 1930s downstream from the natural lip, raising the water level by about 3 m.

A series of recessional moraines up-valley from the Kalispell moraine record temporary standstills or minor re-advances of the glacier during downcutting of the lake outlet. A smaller glacial lake was impounded northwest of Glacial Lake Flathead during this retreat. Failure of its dam near Tally Lake cut a gorge in the area and deposited the Lost Creek fan on the west side of the Flathead Valley (Smith, 2004).

Glacial Lake Kootenai formed during retreat of the Purcell Lobe of the Cordilleran Ice Sheet from its LGM position along the Clark Fork River at Pend Oreille (Alden, 1953). As ice retreated from the Kootenai River basin, multiple lakes formed in the mountain valleys; the river was ultimately impounded near Bonners Ferry (Langer and others, 2011). Glaciolacustrine silt overlies till and terraces in the valley (Alden, 1953). Prior to topping the nearby passes, 30–90 m (100–300 ft) of silt and sand accumulated up to altitudes of 700 m (2,300 ft). As the glacier continued to recede, eventual outflow from the lake occurred at heights of about 670 m (2,200 ft), southward down the Purcell Trench, and south of Troy, Montana, along the Bull River drainage towards the Clark Fork River (figs. 2, 8).

### *5.1.4 Eolian Deposits*

Significant deposits of Quaternary eolian sediments have been mapped in the Flathead Valley north of Flathead Lake (Konizeski and others, 1968; LaFave and others, 2004). Stabilized barchan dunes in the valley are locally interbedded with the Glacier Peak "G" tephra at 13.6–13.3 cal ka BP (LaFave and others, 2004). The dune field formed after Glacial Lake Kalispell lowered and apparently before vegetation could be reestablished across much of the valley.

### *5.1.5 Alluvial Deposits and Landforms*

Alluvial deposits in the intermontane valleys of northwestern Montana consist of high-bench gravels and glacial outwash from the last glaciation, deposited mostly as alluvial fans, Holocene terrace sand and gravel, and recent alluvium. In the Flathead River drainage, post-glacial alluvial deposits are mostly incised into glacial sediments north of Flathead Lake, and into Glacial Lake Missoula deposits south of the lake. Incision along the Flathead River upstream from the lake, typically less than 10 m, produced two or three terraces near Columbia Falls and Kalispell. South of Kalispell, the Flathead River developed high sinuosity as it built a fluvial-dominated delta into Flathead Lake. South of the lake, the Flathead River has downcut through as much as 150 m of Glacial Lake Missoula deposits upstream from the town of Dixon. A terrace about 10 m above the modern Flathead River contains the 13.6–13.3 cal ka BP Glacier Peak "G" tephra, showing that most of the downcutting occurred in late Pleistocene to early Holocene time (Levish, 1997; Edwards, 2006). Much of this downcutting is assumed to have occurred during high-energy discharge during the draining of Glacial Lake Missoula and the smaller Glacial Lake Flathead (Smith, 2004; Edwards, 2006; Hendrix, 2011).

Along the Clark Fork River below its confluence with the Flathead River and upstream to the Missoula Valley, narrow post-glacial terraces form low-relief landforms where the rivers have cut into Glacial Lake Missoula deposits and bedrock canyons (Smith and others, 2011). In the Little Bitterroot River Valley and the Clark Fork River Valley near the city of Plains, wide areas of glacial lake silt were downcut, producing a few terraces.

### *5.1.6 Hillslope Deposits and Landforms*

Hillslopes in northwestern Montana were steepened by glacial erosion. During glacial retreat, hillslopes were commonly modified by paraglacial mass movement processes, the reaction of the landscape to deglaciation. One such major landslide, a rock avalanche, was mapped in the Flathead Valley. The rock avalanche distribution was deposited next to kettles on the landscape, indicating the landslide occurred during deglaciation when the present lakes were still occupied by mounds of ice (Smith, 2001). At this time, no comprehensive studies of hillslope failures have been done. Local examples have been studied in some detail, including landslide damming of lakes (Butler and others, 1991; Pierce and others, 2014a), and formation of Quake Lake by seismogenic shaking (see other chapters in this volume; Matthews, 1960).

### *5.1.7 Pleistocene Mammal Localities*

Within the Clark Fork River Basin, late Cenozoic vertebrate localities provide some information about changing Tertiary–Quaternary ecosystems. For example, mammal fossils have been reported by Rasmussen (1974b) and Dundas (1990), building on earlier studies by Hay (1924), McLaughlin and Konizeski (1952), and Konizeski (1957). The late Pliocene or early Pleistocene fauna are *Castor* (beaver, Clark Fork Locality No. 1) and *Equus* (horse, Clark Fork Locality No. 2) (Konizeski, 1957; Kay and others, 1958; Rasmussen, 1974b). McLaughlin and Konizeski (1952) reported the recovery of a gomphotherid with bunomastodont molars in deposits potentially temporally related to Pleistocene Glacial Lake Missoula. The find was later assigned to the Pliocene ("Trilophodon-type shovel-tusker mastodon from unconsolidated sands and gravels" in Honkala, 1958 and *Amebelodon* cf. *A hisksi* in Kay and others, 1958). Local faunas from the Deer Lodge and Bitterroot Valleys have been assigned to the Hemphillian (containing cf. *A. hicksi*) and the Clarendonian (with "*Mammut Pliomastodon* cf. *P. matthewi*," Kay and others, 1958). At the time these were assigned to the Pliocene; Hemphillian and Clarendonian faunas are now considered late Miocene. The faunal assemblages from Clark Fork No. 3 (Bert Creek no. 9, MV6555), Clark Fork No. 6 (Dutton Ranch no. 3, MV6615), Clark Fork No. 11 (Dutton Ranch no. 4, MV6616), Clark Fork No. 12 (Dutton Ranch no. 6, MV6618), Clark Fork No. 7 (MV6626, Dutton Ranch no. 8), and MV8702 were collectively designated as the late Pleistocene. Other late Pleistocene localities include Clark Fork Locality No. 4 (MV6601, Carter Creek no. 1), Clark Fork No. 5 (MV6602, Garden Gulch no. 1), and Clark Fork No. 8 (Flint Creek no. 14, KU-Mt-61). Possible late Pleistocene or early Holocene localities include Clark Fork No. 9 (Drummond no. 1, MV6510), Clark Fork No. 10 (Flint Creek no. 7, MV6605), and Clark Fork No. 13 (Warm Springs no. 1, KU-Mt-3; Rasmussen, 1974b).

## 5.2 Southwest

### *5.2.1 Overview*

The mountains and intermontane valleys of southwestern Montana (fig. 4), from the Bitterroot Range and Beaverhead Mountains on the west, to the Spanish Peaks on the east, and from the Centennial Mountains on the south, to the Garnet Range on the north, were unaffected by continental glaciations. Evidence for valley glaciers in many of the mountains include cirques, U-shaped valleys, lateral and terminal moraines, and outwash fans. Alden (1953) mapped many localities in the region and described older and younger moraines and outwash plains extending beyond valley glaciers. Multiple stream terraces are common in the axial and tributary valleys. Quaternary deposits are thin, mostly less than 15 m (50 ft) thick. Mountains of southwestern Montana hosted ice caps during the LGM, including those in the East Pioneer and Flint Creek ranges and the Boulder Highlands (fig. 10). Valley glaciers extended onto surrounding piedmonts from the Flint Creek Range and possibly others.

The Quaternary stratigraphy of the intermontane valleys prior to the last glaciation is poorly known. Widespread surface exposure of Tertiary (Paleogene and Neogene) sedimentary rocks and subsurface mapping show that the overlying Quaternary units are generally <30 m (100 ft) in all of the valleys. This indicates that the Quaternary was generally a time of erosion rather than sedimentation in the intermontane valleys.

*5.2.2 Glacial Deposits and Landforms*

Mountain glacier deposits have been mapped regionally (Alden, 1953; Locke and Smith, 2004), but detailed work is sparse. Based on regional mapping of southwestern Montana mountains, Alden (1953) described deep erosional pits on boulders of older tills in some valleys, and fresher boulders in younger tills. More recent mapping (Pierce, 1979) in the West Yellowstone area provides clues to recognition of LGM and older deposits in the region (see section on southeastern and south-central Montana). Marine isotope stage (MIS) 2, or Pinedale-age tills, have pronounced hummocky, knob-and-kettle topography, exposed boulders, weak soils, and thin weathering rinds. In contrast, MIS 6, or Bull Lake-age tills, form more subdued landforms with fewer exposed and weathered boulders and better developed soils (Waldrop, 1975; Pierce, 1979). Regional or detailed mapping that distinguished Pinedale, Bull Lake, and/or older glacial deposits has been published for the Centennial Mountains (Pierce and others, 2014a) and parts of the Beaverhead Mountains (Weber, 1972; Lonn and others, 2013).

Mountain glaciers formed to significant depths across a number of ranges. Local ice caps in the East Pioneer Range, Basin area, Anaconda Range, Flint Creek Range, and Madison-Gallatin Ranges controlled ice flow directions, such that flow was not always constrained by the underlying topography. Ice accumulation was affected by aspect, and was shown to have shifted over time in a few of these ice caps (Ruppel, 1963; Pierce, 1979; Zen, 1988).

*5.2.3 Glacial Lakes*

Aside from Glacial Lake Missoula, impoundments of water in valley glacier systems were common, but sparsely noted in southwestern Montana. One example is in the east-facing Fish Creek drainage in the Highland Mountains (Dresser, 1996). Apparently water was impounded in a tributary valley by an ice dam during retreat of the main glacier in the Fish Creek Valley. Failure of this ice dam caused catastrophic flooding toward the east, forming an apron of gravel across streamlined hills that are scattered boulders along Hwy 41 southwest of Whitehall, Montana (fig. 10).

In the Centennial Valley of southwestern Montana, drainage originally flowed to the northeast until large landslides blocked and dammed it during the late Pleistocene, creating Lake Centennial (Pierce and others, 2014a). The lake has lowered through time to the surface level of the present lakes.

*5.2.4 Eolian Deposits*

Significant eolian deposits have been mapped in the Centennial Valley where extensive dunes and sand sheets occur north and west of Red Rock Lake. Wind from the south and west during the late Pleistocene and Holocene carried sediment from receding shorelines of Lake Centennial, building tall dunes (Pierce and others, 2014a). Reactivation of the dune field is indicated by paleosols in the dune sequences that have organic A horizons on the order of hundreds of years old (Kenneth L. Pierce, written commun., 2019).

*5.2.5 Alluvial Deposits and Landforms*

Quaternary alluvium along stream valleys occurs along channels and floodplains and on terraces along river valleys. Regional studies of stream patterns and fluvial histories in southwestern intermontane valleys are few (e.g., Jorgensen, 1990). Barkman (1984) hypothesized that the longitudinal profile in the Bitterroot River Valley between Hamilton and Stevensville is affected by Holocene tectonism, which is being expressed by an increase in braiding along that reach.

Fluvial terraces and the Cedar Creek alluvial fan of the Madison River and its tributaries, downstream from Quake Lake, represent classic landforms. The

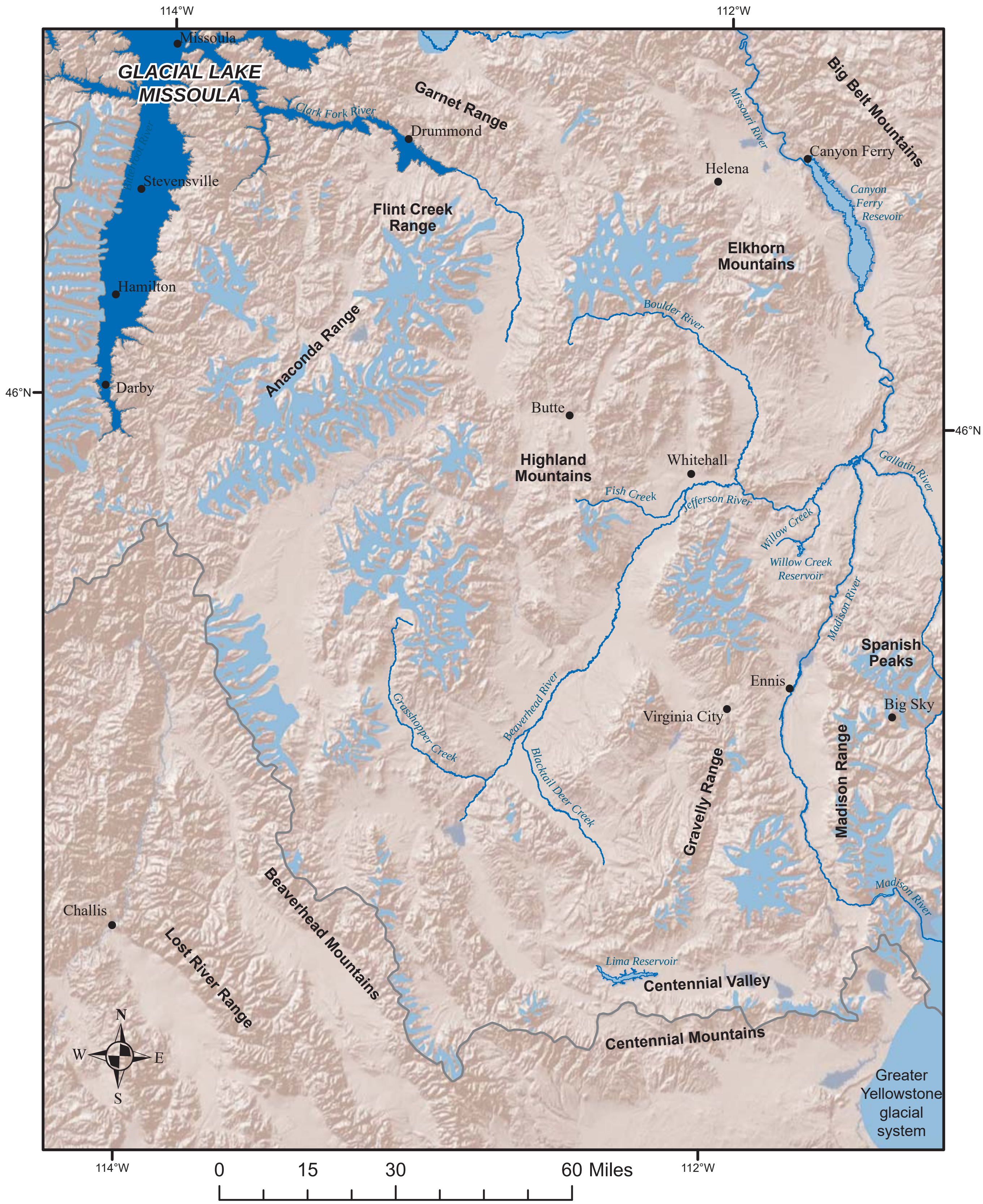



Figure 10. Southwestern Montana glacial extents (light blue) and features mentioned in the text.

Cedar Creek alluvial fan that slopes from the Madison Range towards the Madison River south of Ennis (fig. 2) has classic fan shape and symmetry (Ritter and others, 1993). The fan underwent periods of aggregation from glaciofluvial outwash and upper-fan incision. Correlation of fan surfaces to Bull Lake and Pinedale-age glacial deposits up valley show that the surfaces aggraded during glacial times, and incised during deglaciation (Ritter and others, 1993). Quaternary tectonic uplift has led to periods of aggradation and intermittent downcutting, forming flights of late Pleistocene to Holocene terraces (Bearzi, 1987). Deglaciation of the Madison Range after the LGM initiated incision of the Cedar Creek fan.

### *5.2.6 Hillslope Deposits and Landforms*

Hillslopes in the intermontane valleys of Montana show evolutionary patterns related to climate involving both mass movements and aspect-related processes. Landslides have been mapped locally on most of the 1:100,000 and larger-scale maps. At this time, no comprehensive studies of these hillslope failures have been done. Local examples have been studied in some detail, including recent failures related to intense weather events (Schuster and others, 1995; Brown and Hyndman, 2000; Hyndman and Brown, 2000), and the extensive mass movements in the Gravelly Range (Shaw, 1986) have been shown to have moved due to seismic triggering (Carrara and O'Neill, 2003).

Regional mapping and local observations show strong influences of aspect-related hill slope processes, soil development, and plant-life controls on the character of slopes in the western USA (Poulos and others, 2012). These features can be seen in the valleys of the Bitterroot Range (Beaty, 1962), the eastern Deer Lodge Valley, and other locations where tributaries to the axial drainages have incised weakly consolidated, mostly Tertiary-age sedimentary rocks. The amount of glacial headwall erosion in the Bitterroot Mountains was profoundly affected by aspect (Naylor and Gabet, 2007). In many areas southwestern aspects have steeper slopes than northeastern slopes.

Large forest fires are known to increase the likelihood of erosion, alluvial fan sedimentation, and production of debris flows during rainfall or snowmelt events in burned-over forests. Studies in small watersheds in the Bitterroot Valley have led to the quantification of these processes (Gabet and Bookter, 2008; Riley and others, 2013; Hyde and others, 2014). Post-fire alluvial fans initially aggraded and then were incised. The dispersal of trees across the fans affected sediment accumulation for decades (Short and others, 2015).

### *5.2.7 Pleistocene Mammal Localities*

Fossil remains have been recovered from the stream systems of the Gallatin, Madison, and Jefferson Rivers in southwestern Montana. Fossils of *M. columbi* have also been collected from Alder Gulch, near Virginia City (Hayden, 1872; Hay, 1924; Hill, 2006). A late Pleistocene fauna containing *Miracinonyx (Acinonys)*, *Camelops, Bison,* and *Ovis* has been recovered from the Sheep Rock Spring locality west of the Boulder River (Wilson and Davis, 1994; Wilson and others, 2015). Excavations at Sheep Rock Spring revealed a fourfold sequence of late Quaternary deposits, including: a basal boulder diamict marking a rock avalanche of angular clasts from the tor; diamicts and stratified sediments from down-valley debris flows; late Pleistocene to early Holocene channel and overbank alluvium with a paleosol ~11.5 cal ka BP (~10.0 $^{14}C$ ka BP); and a Holocene cross-valley alluvial/colluvial fan, reflecting intermittent deposition and lowered effective vegetative cover (Wilson and others, 2015). The sequence reflects local events superimposed upon a regional early Holocene climate signal. The bones of extinct megafauna are in interstitial sediments among the landslide boulders, but a date of ~23 cal ka BP (~20.7 $^{14}C$ ka BP) on residual bone organics is problematic because of an unusual $^{13}C/^{12}C$ ratio.

Elsewhere in southwest Montana, fragments of *Mammuthus* have been reported from the Horse Prairie–South Everson Creek area (Bonnichsen and others, 1987, 1990), and *Bison occidentalis* was found at Madigan Gulch, a tributary to Grasshopper Creek in the Beaverhead River drainage (Nichols, 1979). *Canis dirus* is known from Orr Cave in the Blacktail Deer Creek Valley (Campbell, 1978; Kurten, 1984). Remains of some small mammals and fragments of tusk have been reported from the Centennial Valley (Hibbard in Honkala, 1949; Bump, 1989). Also, in the Centennial Valley, on the west side of Lima Reservoir, faunal remains dating from about 50,000 to 21,000 cal yr BP (50,000 to 19,000 $^{14}C$ yr BP) have been recovered from swamp, paludal, lacustrine, fluvial, and debris flow deposits (Bump, 1989; Dundas, 1992; Dundas and others, 1996; Hill and others, 1995; Hill and Albanese, 1996; Hill, 1999a,b; Hill and Davis, 2005). The mammalian fauna includes *Mammuthus, Equus, Camelops, Odocoilheus, Antilocapra, Bison,* *Ursus, Homotherium serum, Canis latrans, Canis lupus, Spermophilis, Castor canadensis*, and *Ondatra zibithicus* (fig. 11; cf. Dundas and others, 1996; Hill, 2006). Centennial Valley was an area of active tectonic activity during the late Quaternary (Anastasio and others, 2010; Pierce and others, 2014a), and a record of environmental change since Wisconsin or Pinedale time suggests that prior to 17,000 cal yr BP Centennial Valley resembled a modern alpine tundra (Mumma and others, 2012). From 17,000 to 10,500 cal yr BP the environment may have resembled subalpine parkland, followed by a warmer, drier climate until 7,100 cal BP (Mumma and others, 2012). In the nearby Beaverhead River Canyon, U-series dates suggest that three terrace levels may correspond to a Pinedale glaciation, the Bull Lake glaciation, and the intervening Sangamon interglaciation (fig. 7B; Bartholomew and others, 1999).

## 6. ROCKY MOUNTAIN FRONT AND THE NORTHERN GLACIATED PLAINS

### 6.1 Pre-Glacial Deposits

Local unglaciated areas north of the glacial limits in the Plains region (fig. 4) were not overridden by the Laurentide Ice Sheet (fig. 12). The Pliocene (or upper Miocene?) high-level gravels including the Flaxville Formation (or Gravels; Colton, 1955, 1962) and the Wiota Gravel (Jensen, 1951, in Colton, 1962) are considered pre-glacial deposits in northern Montana and adjacent parts of Saskatchewan and Alberta (fig. 13). Although these deposits may be as old as late Miocene, they are part of the modern landscape and merit inclusion here. The gravel deposits unconformably overlie the Paleocene Fort Union Formation and older bedrock units. The poorly consolidated sandy gravel consists of quartzite and siltite clasts (Colton and

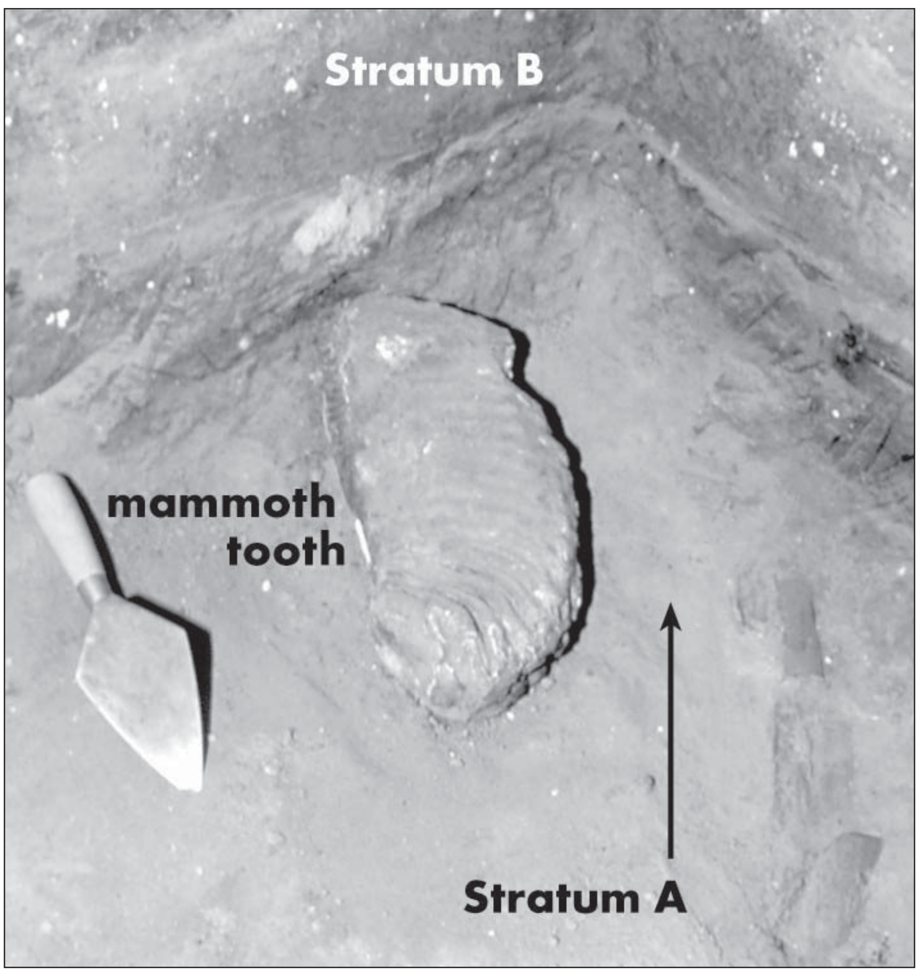



Figure 11. Mammoth fossil tooth found in place along an unconformity and buried by organic deposits interpreted as having been formed in a marsh, with organics radiocarbon dated to 42,000 cal yr BP (37,000 $^{14}$C yr BP) (early Pinedale?) in the Centennial Valley, southwestern Montana (Hill and Davis, 2005).

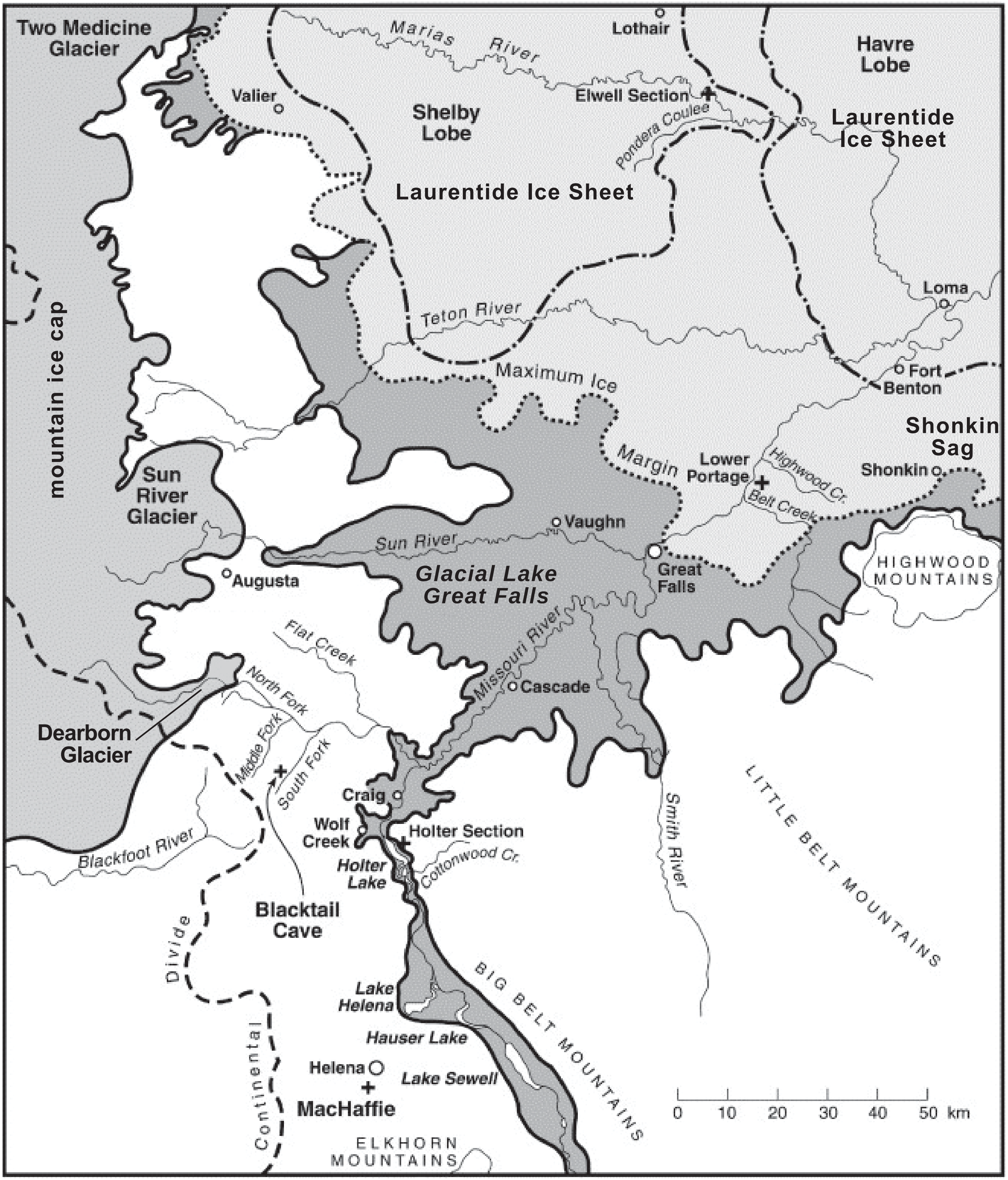



Figure 12. Locations of sites near glacial Lake Great Falls mentioned in the text (extent of glacial Lake Great Falls adapted from Montagne (1972); Laurentide Ice Sheet, light gray; Rocky Mountain Ice Cap, medium gray; glacial Lake Great Falls, dark gray.

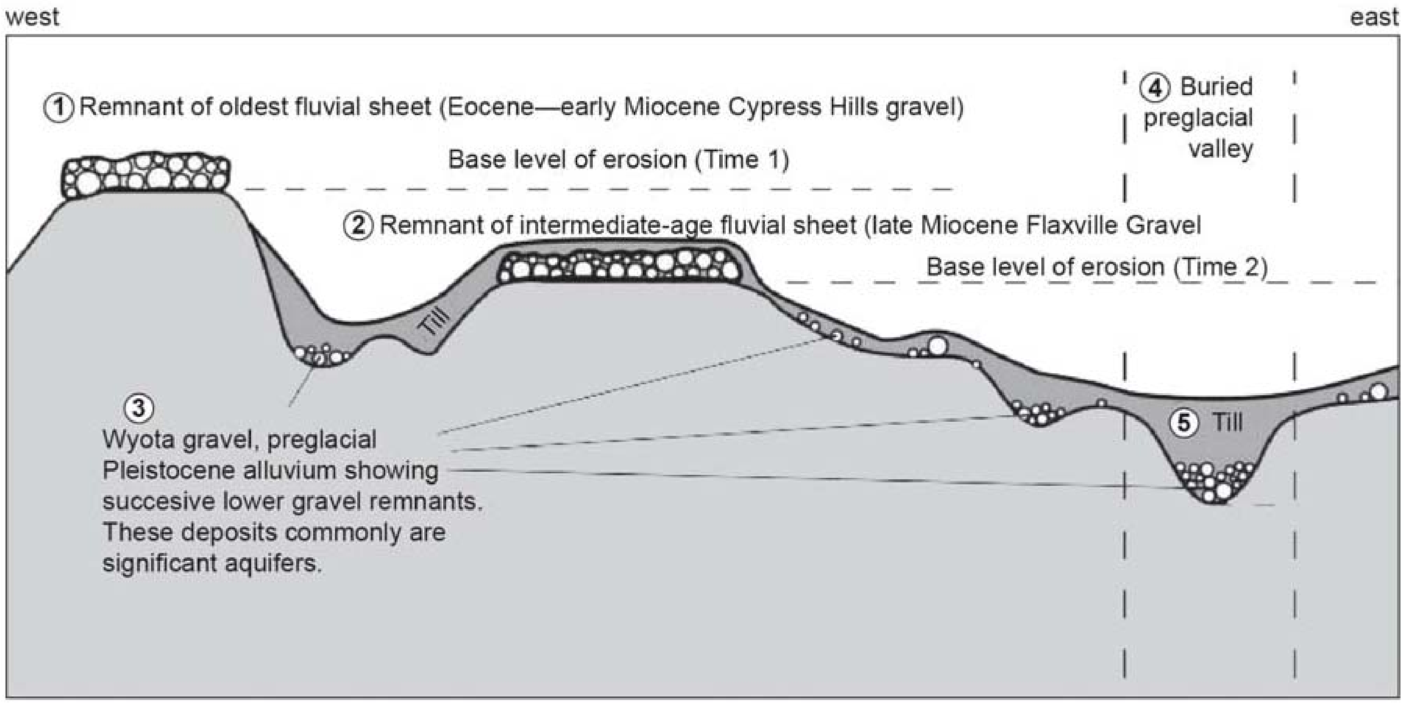



Figure 13. Illustration depicting the stratigraphic position, relative age, and relative position of Rocky Mountain derived quartzite-rich gravel during Tertiary erosion in the Great Plains of northern Montana and Canada; modified from Cummings and others (2012); numbers indicate sequence through time.

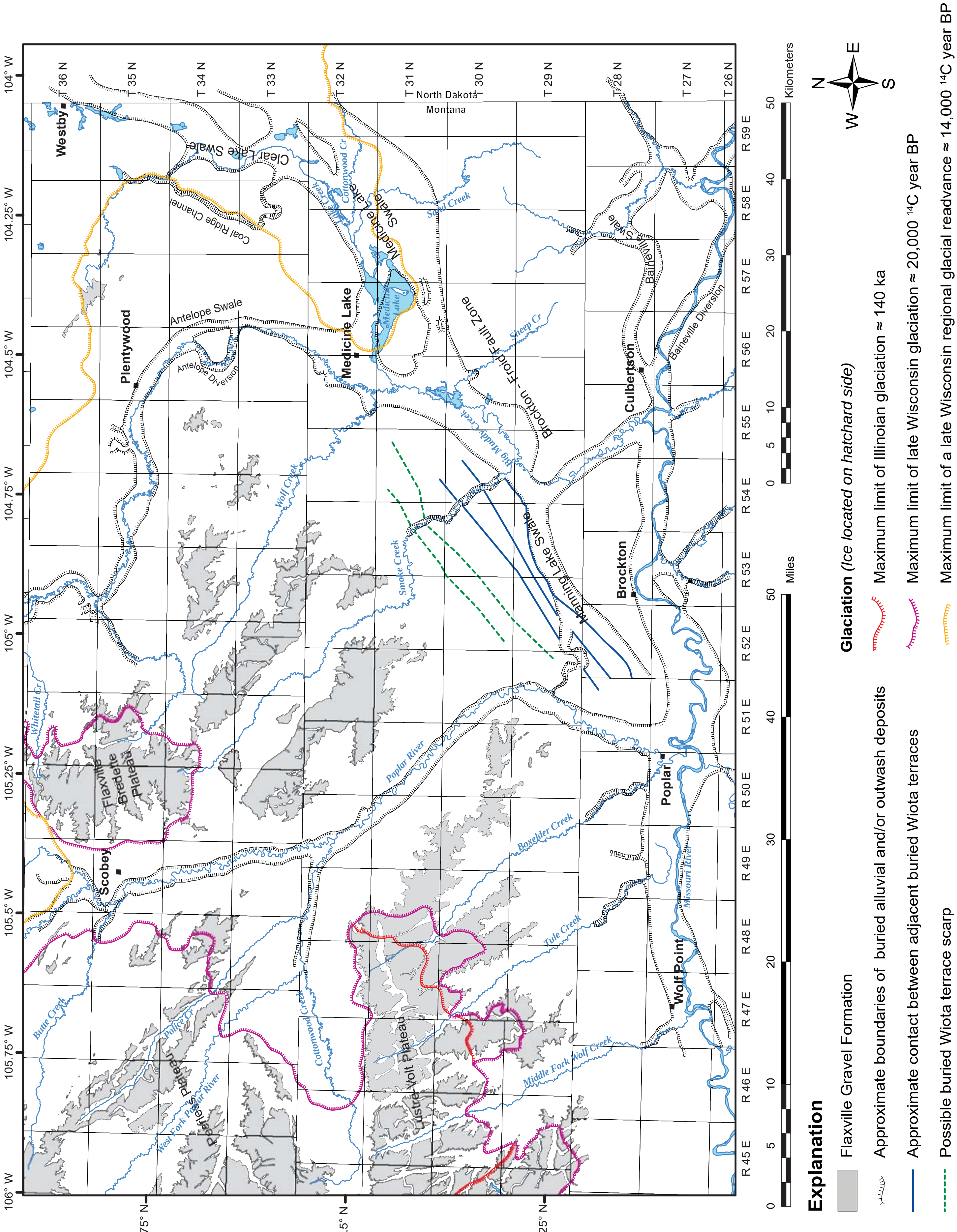
Patton, 1984) derived from Belt Supergroup rocks in the northern Rockies. The Flaxville and Wiota gravels are younger than similar units in southern Canada. All of these units were deposited by northeast-flowing streams. Buried beneath the surficial glacial and alluvial cover are pre-glacial alluvial valleys (fig. 14; Donovan and Bergantino, 1987; Reiten and Chandler, 2014; Reiten and Bierbach, 2016). As these valleys are known by only drilling records (Reiten and Chandler, 2014) the distribution and age of these channels are best known where they have been developed as aquifers.

Pre-glacial routing of the Missouri River near Great Falls (fig. 15) and the major tributaries to the Missouri were initially mapped by Calhoun (1906). Several broad swales have been mapped in detail in northeastern Montana (fig. 14). Whereas some of these buried valleys are pre-glacial routes of the Missouri River and its tributaries (fig. 15), some were modified or formed by subglacial drainage of meltwater. The Manning Lake swale and the Medicine Lake swale trend southwest to northeast, delineating the valley of the preglacial Missouri River (fig. 16). The swales are 6–8 mi wide, form relatively low-altitude and low-relief areas, and were inherited from the preglacial drainage systems. The Clear Lake swale is 3–4 mi wide trending north to south, filled by meltwater channels and glacial outwash deposits. Buried valleys of the northeast-flowing ancestral Missouri River underlie the Medicine Lake swale, and south-flowing glacial meltwater channels underlie the Clear Lake swale. The modern drainage system is not aligned with the pre-glacial drainage of the Missouri River, which flowed northeast to Hudson Bay and the Labrador Sea (fig. 16). Tectonic uplift in Canada, Quaternary glaciation, and stream piracy in the USA resulted in drainage eventually directed to the southeast and ultimately south (Cummings and others, 2012).

### 6.2 Glacial Deposits and Landforms

Advance of continental glaciers into Montana occurred in generally north-to-south directions as the Montana Lobe of the Keewatin Ice Sheet (Calhoun, 1906) and by northeast to southwest flow as the Laurentian Ice sheet at different times (fig. 17). The ancestral Missouri River and many of its tributaries were diverted southward by advance of continental glaciers. Glacial flow was diverted around the Sweetgrass Hills of Montana and the Cypress Hills of southern Alberta and Saskatchewan (Fullerton and others, 2004b).

Figure 14 (opposite page). Physiography of northeastern-most Montana showing distributions of Flaxville Gravel Formation, locations of buried alluvial and/or outwash deposits, and topographic swales. Limits of glaciations are from Fullerton and others (2004b); modified from Reiten and Bierbach (2016). Although some of the deposits are pre-Quaternary, they relate to the pre-glacial landscape.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North Dakota
Montana
Westby
Clear Lake Swale
Coal Ridge Channel
Medicine Lake Swale
Medicine Lake
Plentywood
Antelope Swale
Antelope Diversion
Brockton - Froid Fault Zone
Culbertson
Bainville Swale
Baineville Diversion
Manning Lake Swale
Brockton
Poplar
Wolf Point
Scobey
Flaxville Bredette Plateau
Peerless Plateau
Lustre-Volt Plateau
Sand Creek
Sheep Cr
Big Muddy Creek
Wolf Creek
Smoke Creek
Poplar River
Boxelder Creek
Tule Creek
Missouri River
Middle Fork Wolf Creek
Cottonwood Creek
Cottonwood Cr
Butte Creek
Police Cr
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10
20
30
40
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Kilometers
Miles
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Explanation
Flaxville Gravel Formation
Approximate boundaries of buried alluvial and/or outwash deposits
Approximate contact between adjacent buried Wiota terraces
Possible buried Wiota terrace scarp
Glaciation (Ice located on hatchard side)
Maximum limit of Illinoian glaciation ≈ 140 ka
Maximum limit of late Wisconsin glaciation ≈ 20,000 ¹⁴C year BP
Maximum limit of a late Wisconsin regional glacial readvance ≈ 14,000 ¹⁴C year BP

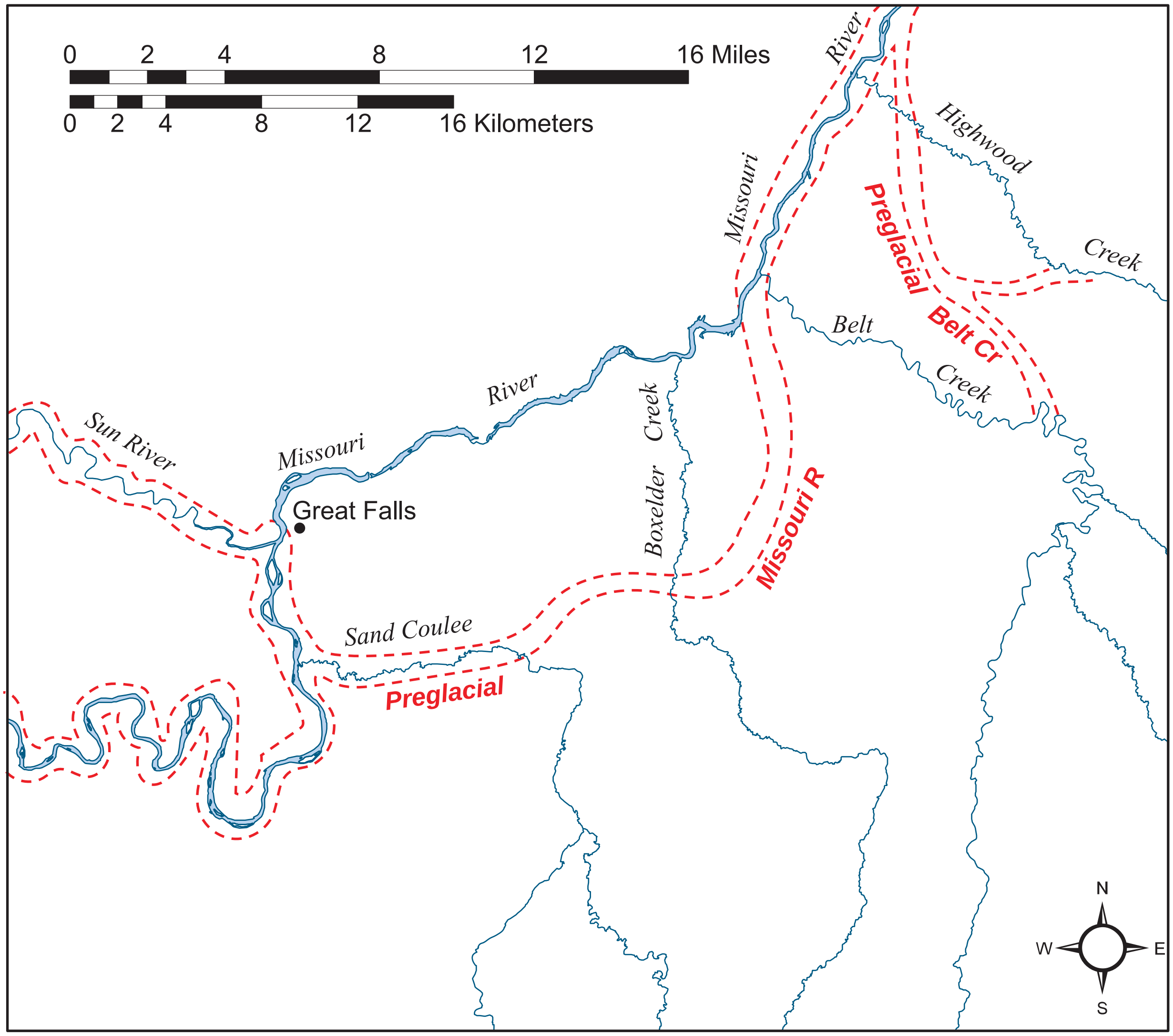


Figure 15. The pre-glacial course of the Missouri River was about 23 km south of the present course. This northward shift in the river position after deglaciation is opposite that generally produced by the southward advance of the continental ice sheet. This rerouting of the river in the Great Falls area was initially recognized by Calhoun (1906).

Because the glaciers were flowing on Cretaceous shale and basal shear stresses were low, ice-surface slopes were thus low and flow diverted around topographic mounds (Mathews, 1974). The longitudinal profiles of some of the subglacial deposits are undulatory, indicating some originated as or were modified by tunnel channels. Pressurized water flowing in pressurized subglacial drainage channels are known to have modified the bases of many late Pleistocene glaciers (O'Cofaigh, 1996).

The glacial deposits along the Rocky Mountain Front east of Glacier National Park contain sequences of pre-LGM or pre-Wisconsin till and interbedded paleosols, the oldest known glacial deposits in Montana. The best records of pre-Bull Lake (pre-MIS 6) glaciations in the Rocky Mountains are on high terraces such as the Mokowan Butte, Saint Mary Ridge, and Two Medicine Ridge on the eastern slope of the Northern Rockies, near the Canada–USA border (fig. 7B; Cioppa and others, 1995; Karlstrom, 2000; Pierce, 2003). In this area of northern Montana and southern Alberta, multiple glacial deposits and paleosols have been correlated to MIS 6 and older glaciations (Horberg, 1954, 1956; Karlstrom, 1987, 1991, 2000; Cioppa and others, 1995) based on soil development and magnetostratigraphy.

Little work has been published on LGM and penultimate glacial deposits along the Rocky Front, other than mapping (Fullerton and others, 2004a; Berg, 2008). Work in Alberta suggests that the continental glaciers extended to near the Rocky Mountain Front in Alberta only during the last glaciation, but not during the penultimate glaciation of MIS 6 (Little, 1995; Jackson and others, 1996, 1999, 2008, 2011; Gowan, 2013). This conclusion is in contrast to earlier work in which deposits considered to be of LGM and an ear-

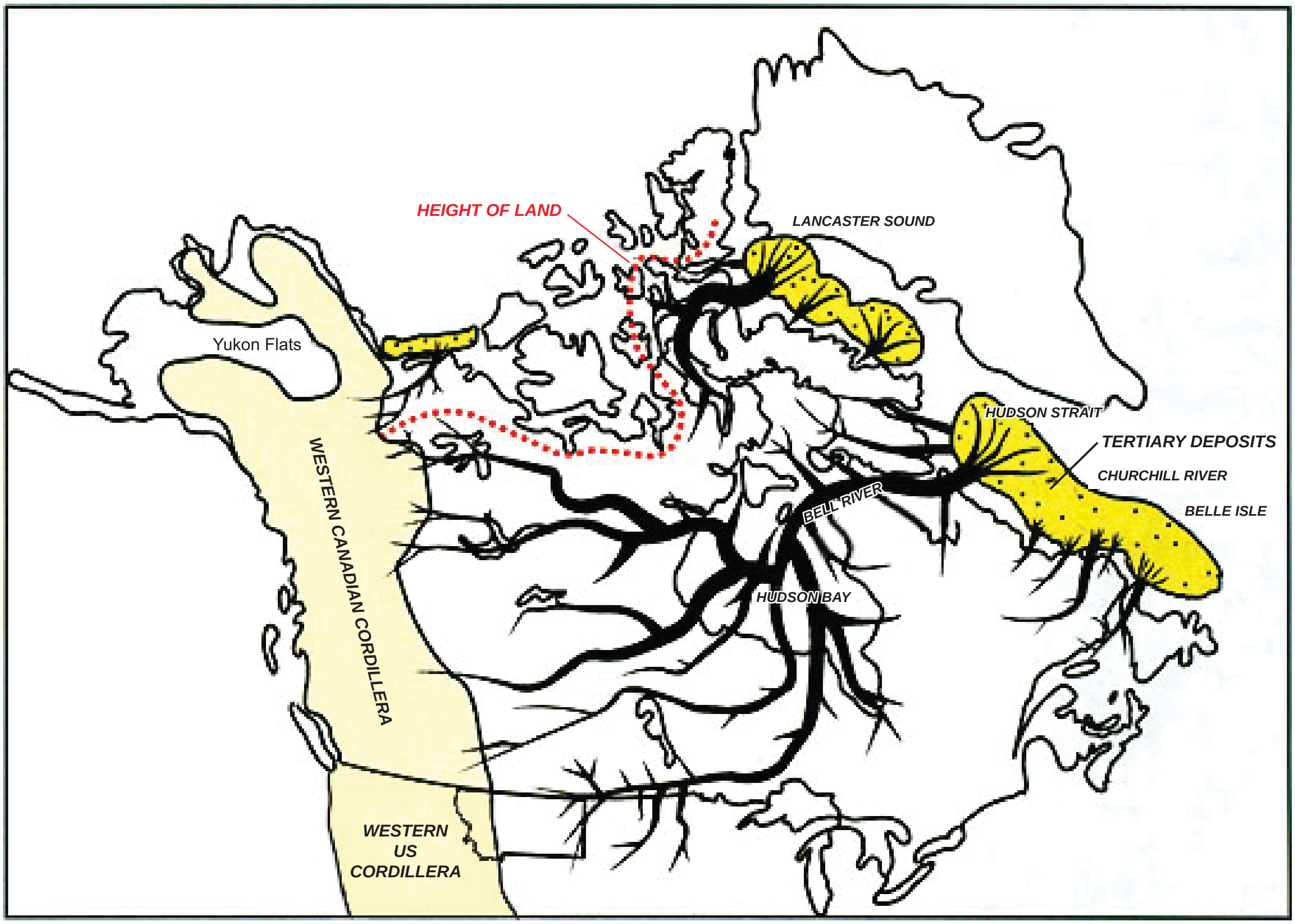


Figure 16. Conceptual depiction of Tertiary (pre-glacial) drainage in northern and United States and Canadian prairies; modified from Cummings and others (2012); Montana shown by outline.

lier advance of the Laurentide ice sheet were mapped as Wisconsin (or Wisconsinan) and pre-Wisconsin in age (Alden, 1932; Fullerton and others, 2004a). Optical dating of glaciolacustrine deposits of Glacial Lake Great Falls that are interbedded with till showed that they are all post ~25 ka, indicating that the stratigraphically earlier and later lakes were related to the advance and retreat of the ice sheet during the last glaciation (Feathers and Hill, 2003).

### 6.3 Glacial Lakes

Impoundment of proglacial lakes by the Cordilleran and Laurentide ice sheets and smaller mountain glaciers led to deposition of sandy and silty lake sediments in intermontane valleys and paleovalleys on the plains (fig. 3). Most of the lakes discharged rapidly as the ice dams failed, forming distinctive large-scale bedforms, erratic boulder trains, and erosional features, especially within and downstream from Glacial Lakes Missoula and Great Falls (Alden, 1932, 1953; Pardee, 1942; Smith, 2006; Davis and others, 2006; Alho and others, 2010).

Advance of continental glaciers southward during each Quaternary glaciation probably diverted and impounded north-flowing stream systems. As first mapped near Great Falls, the Missouri River was blocked by the Keewatin (or Laurentide) ice sheet, forming Glacial Lake Great Falls (fig. 17; Calhoun, 1906; Alden, 1932; Montagne, 1972; Hill, 2000). Northwest of Great Falls at Hower Coulee, a section of fluvial gravels overlain by lacustrine silt, then till of the Laurentide ice sheet, and a second section of lacustrine silt suggests two episodes of lake development separated by a glacial episode. Preliminary optically stimulated luminescence (OSL) ages on the section show that deposition took place during MIS 2 between about 14 and 24 ka (figs. 7A, 18; Feathers and Hill, 2003), rather than during both MIS 2 and MIS 6, as proposed by other workers (Fullerton and others, 2004b). At times the lake extended from south of Great Falls upstream to the Canyon Ferry area (Mon-

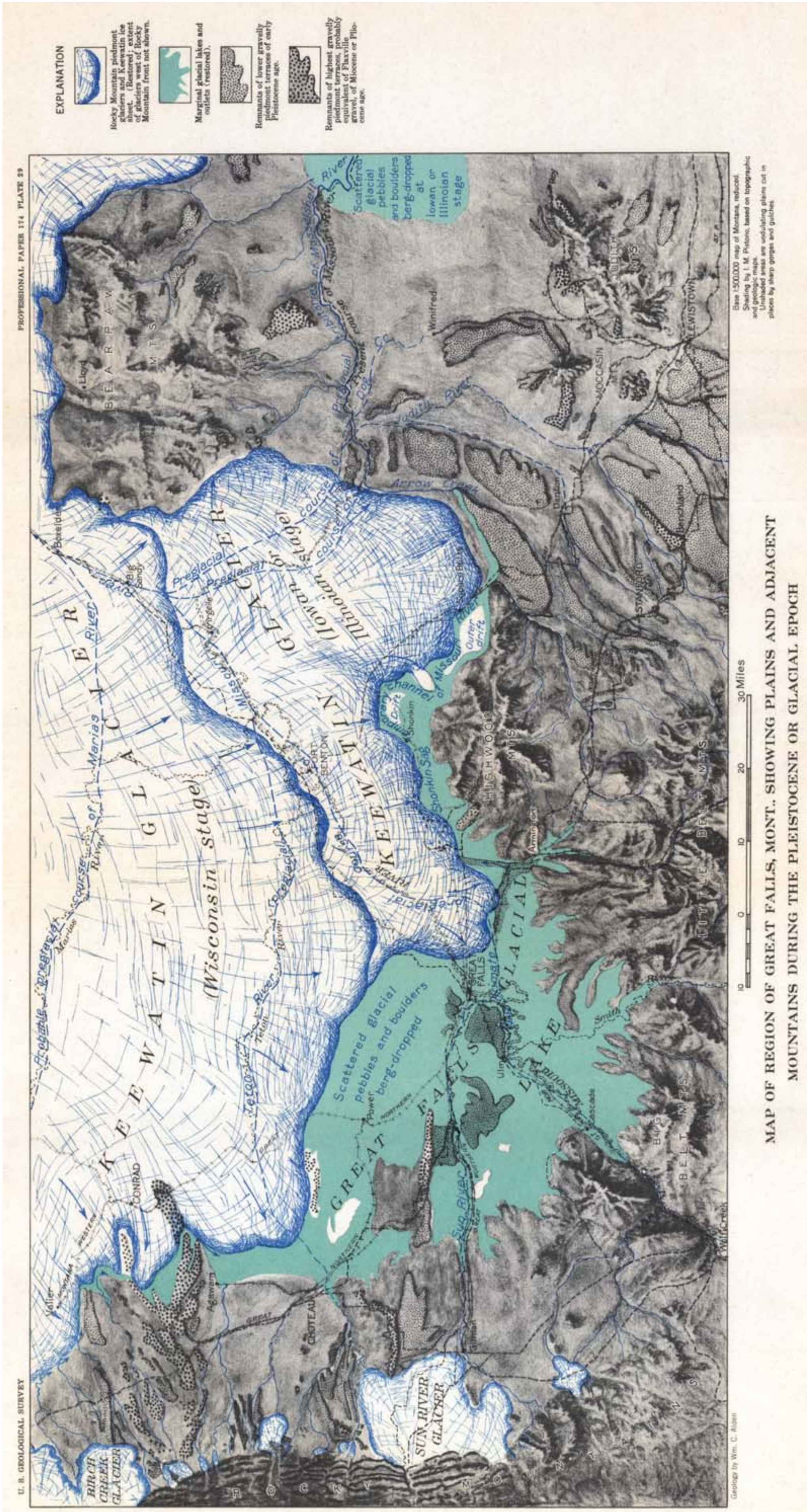


Figure 17. Map of the Keewatin glacier damming the Missouri River to form glacial Lake Great Falls; from Alden (1932). See text for discussion of the ages of glacial deposits.

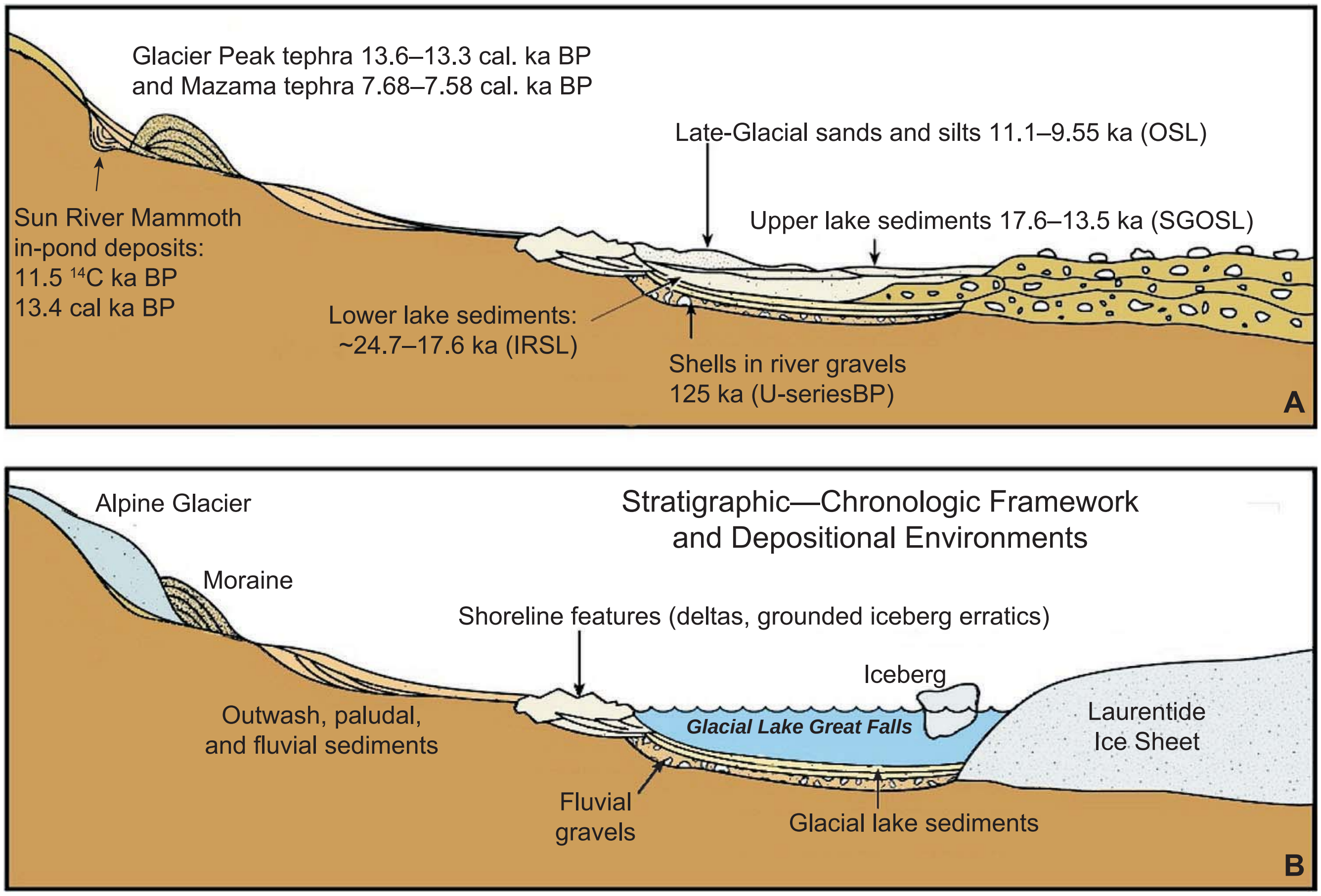


Figure 18. Schematic cross sections of glacial Lake Great Falls. (A) Numerical ages from Feathers and Hill (2003) were revised by Hill and Feathers (2019) and Hill and Feathers, unpublished data; (B) stratigraphy (from Hill, 2006). In the Sun River area mammoth remains found in organic deposits date to around 13,400 cal yr BP (11,500 $^{14}$C yr BP) and are overlain by sediments that contain volcanic tephras. Luminescence ages of glacial lake deposits suggest a late Wisconsin age for the glacial ice margin (cf. Hill and Feathers, 2002). Shells underlying the lake deposits are about 125,000 years old from using U-series analysis; OSL, optically stimulated luminescence dating (of quartz); SG OSL, single grain optically stimulated luminescence dating (of quartz); IRSL, infrared stimulated luminescence (of K-feldspar); 14C, carbon-14 dating (uncalibrated).

tagne, 1972). Fullerton and others (2004b) suggested that separate lakes filled the basin possibly from the early and middle Pleistocene (pre-Illinoian and Illinoian) to the late Pleistocene (fig. 7). However, OSL dates for laminated lacustrine silts in the Helena to Great Falls area indicate that both the lower and upper lake sediments of Glacial Lake Great Falls were deposited during MIS 2, late Wisconsin or Pinedale time (figs. 7, 18; Hill and Valppu, 1997; Hill and Feathers, 2019). These dates imply that a lobe of the Laurentide ice sheet extended to and blocked the Missouri River during the latter part of the Wisconsin. Fullerton and others (2012, 2016) extended the late Wisconsin phase of Glacial Lake Great Falls within the Missouri River Valley to southwest of Cascade, at an elevation of 1,142 masl (3,715 ft). They suggested the maximum limit of the Illinoian glaciation as extending beyond the limit of late Wisconsin glaciation (covering Cut Bank, Bynum, Choteau, Power, and Great Falls).

East of the Highwood Mountains, where the outlet of Glacial Lake Great Falls was cut at the Shonkin Sag (fig. 12), Glacial Lakes Musselshell, Circle, and Glendive formed along the southern extent of the ice sheet (fig. 3). Glacial Lake Musselshell does not have distinctive shoreline features or extensive lake-bottom deposits that would indicate long-term stability. Cosmogenic exposure age analysis of clasts dispersed at many altitudes in the basin showed dates ranging from 20 ka to 11.5 ka (fig. 7A), suggesting that the deposits were carried into the Musselshell drainage by eddies during draining of Glacial Lake Great Falls (Davis and others, 2006).

Glacial Lake Circle formed in the Redwater River Valley and Glacial Lake Glendive formed by impoundment of the Yellowstone River. The history of deposition in Glacial Lakes Circle and Glendive has not been studied in detail (Alden, 1932; Howard, 1958). Fullerton and others (2016) proposed that a maximum age for Lake Glendive can be inferred from a mammoth tooth radiocarbon dated to around 20,000 $^{14}$C yr BP in gravel forming the 12–15 m terrace at Glendive (Hill, 2006).

### 6.4 Eolian Deposits

Significant dune fields of windblown sand deposits were mapped in northeast Montana by Witkind (1959). The vegetation recedes during warm, dry periods, allowing the dunes to reactivate. The largest of the two dune fields covers about 20 mi$^2$ southeast of Medicine Lake, in the northeastern-most part of Montana (fig. 19). The second dune field is located about 10 mi to the southwest between the towns of Froid and Big Muddy Creek. The sand dunes are located southeast of glacial outwash channels. The outwash channels are the likely source of the windblown sand with downwind dune fields established by the prevailing northwest winds.

### 6.5 Hillslope Deposits and Landforms

Hillslopes along valleys of the Plains region show evidence of mass movements associated with slumps and landslides. Most of the landslides are associated with incompetent mudstone and shale deposits in upper Cretaceous Bearpaw, Fox Hills, and Hell Creek Formations and the Paleocene Fort Union Formation. Few of these areas have been mapped in Montana, but extensive mapping in North Dakota documents these deposits (fig. 20).

### 6.6 Pleistocene Mammal Localities

Pleistocene mammalian remains have been reported from localities within the Glacial Lake Great Falls Basin (fig. 18A). The Indian Creek locality, situated on the flanks of the Elkhorn Mountains, contains both the late Pleistocene Glacier Peak (13.6–13.3 cal ka BP) and middle Holocene Mount Mazama (7682–7584 cal. yr BP; Egan and others, 2015) tephras. The stratigraphic sequence contains faunal remains and a series of artifact assemblages (Davis and Greiser, 1992; Albanese and Frison, 1995). Fossils overlying the Glacier Peak tephra (13.6–13.3 cal ka BP) associated with a date of about 12,900 cal yr BP (10,980 $^{14}$C yr BP) include *Bison, Ovis, Marmota*, and *Sylvilagus* (Davis and Greiser, 1992). A terminal Pleistocene or early Holocene faunal assemblage from this locality contains *Bison*, an artiodactyl (cf. *Odocoileus/Antilocapra), Marmota flaviventris*, cf. *Sylvilagus/Lepus, Cynomys ludovicianus*, and *Microtus* (Davis and Greiser, 1992). Also in this same region, remains of *Mammuthus* and *Mammut americana* have been recovered from the Diamond City–Confederate Gulch area, and *Mammuthus* has been found in the vicinity of Helena and Spokane Creek and Spokane Bar (Douglass, 1908; Freudenberg, 1922; Hay, 1924, 1927; Madden, 1981; Hill, 2006). A mammoth tooth from Spokane Bar has been regarded as possibly the northernmost record for *Mammuthus imperator* (cf. Hay, 1927; Madden, 1981, p. 206). Also near Helena, *Bison* has been recovered from Upper Holter Lake and at McHaffie (fig. 18; Melton and Davis, 1999).

Figure 19. Eolian sand southeast of Medicine Lake (fig. 14) forms extensive sheets and barchan dunes.


Figure 20. Landslides occur along the incised Missouri River valley and its tributaries.

The Blacktail Cave contains a significant stratigraphic sequence with fossil remains located near the South Fork of the Dearborn River, between Wolf Creek and Augusta (fig. 18). The cave contains a stratigraphic sequence dating from about 42,000 to 12,000 cal yr BP (37,000 to 10,000 $^{14}$C yr BP; Melton, 1978; Davis and others, 1996; Hill, 1996, 2000, 2006, 2018). A phalanx from a bear (*Ursidae*) recovered from talus beneath a travertine bed, near the top of the stratigraphic sequence, provided a date of 13,000–12,700 cal yr BP (10,930 ± 80 $^{14}$C yr BP; GX-21559). Sediments containing higher amounts of fine-grained clasts, overlain by travertine, contained an artiodactyl dated to 12,490–12,020 cal yr BP (10,270 ± 115 $^{14}$C yr BP; GX-21558) and a bovid dated to 13,290–12,930 cal yr BP (11,240 ± 80 $^{14}$C yr BP; GX-21557). An *Equus* phalanx recovered slightly above a deposit of sand and gravel dates to 31,780–30,650 cal yr BP (27,200 ± 370 $^{14}$C yr BP; GX-21558). The lowest studied sediment consist of mud and clay and is inferred to have been deposited in a cave pool that indicates higher groundwater levels than present, about 42,890–40,340 cal yr BP (37,400 ± 790 $^{14}$C yr BP; Beta-1060101) based on collagen from *Marmota flaviventris*. The vertebrate assemblage found within the late Pleistocene deposits in the cave has a variety of large and small mammals, including: *Bootherium/ Symbos (Symbos cavifrons*, in Melton, 1979; *Bootherium bombifrons*, in Davis and others, 1996), *Bison occidentalis* (Melton and Davis, 1999), *Equus* cf. *conversidens, Odocoileus, Antilocapra, Ursidae, Canis lupus, C. latrans*, *Vulpes, Gulo gulo*, and *Taxidea taxus*. Smaller mammal taxa found in the late Pleistocene sequence in the cave include *Cynomys, Marmota flaviventris, M. caligata, Thomomys, Castor canadensis, Spermophilus, Microtus, Neotoma, N.* cf. c*inera, Phenacomys (paraphenacomys) alpipes*, and *Lepus*.

In the Sun River area (fig. 18A) there are three localities containing the remains of *Mammuthus*. Two localities are in a coulee west of Augusta, and the other locality is a gravel pit west of Vaughn (Marsters and others, 1969; Hill, 2006). One of the mammoths (attributed to *Mammuthus columbi*) found west of Augusta was embedded in organic-rich deposits dated to about 13,400 cal yr BP (11,500 $^{14}$C yr BP; W-1753) and is overlain by Holocene alluvium. Other proboscidean remains mostly attributable to *Mammuthus* from this region of Montana are in the collections of the museum in Shelby, Montana, and the Peabody Museum of Natural History at Yale University, New Haven, Connecticut (Hill, 2006). Hay (1914, 1924) also recorded remains of *Mammuthus* from near Valier, and along the Missouri River (*M. columbi jeffersonii* in Dudley, 1988).

## 7. SOUTH-CENTRAL AND SOUTHEASTERN MONTANA

### 7.1 Overview

South-central and southeastern Montana includes the northern and western parts of Yellowstone National Park and the mountains and valleys of central Montana south of much of the influence of the Laurentide ice sheet. It includes much of the headwater regions of the Yellowstone, Missouri, and Musselshell Rivers (fig. 4).

### 7.2 Glacial Deposits and Landforms

The mountainous Yellowstone–Beartooth region of south-central Montana hosted a large ice cap during glacial periods (Licciardi and Pierce, 2018; Pierce, 1979, 2003; Pierce and others, 2014b). The most complete study of glacial deposits in south-central (as well as southwestern) Montana has been of the areas surrounding Yellowstone National Park (see Licciardi and Pierce, 2018, for a summary). Along the southern and western margins of the Yellowstone Ice Cap system where it extended into Montana (glaciation during MIS 6 or Bull Lake glaciation, dated to about 150 ka; fig. 7B), it produced till and landforms that are farther down-valley than the more recent features of the younger Pinedale glaciation (Richmond, 1957, 1986; Pierce and others, 1976). During the LGM, the outlet glaciers from the Yellowstone Ice Cap converged and extended north down the Paradise Valley to the Eightmile terminal moraines (fig. 21). From the Paradise Valley to Red Lodge, the Pinedale glaciers overrode the Bull Lake terminal moraines (Licciardi and Pierce, 2018; Pierce, 1979; Pierce and others, 2014b). However, in the West Yellowstone area and Jackson Hole, and most other mountain ranges in the Rocky Mountains, the penultimate Bull Lake moraines extend away from the ice cap farther than the later Pinedale moraines. This relationship is unusual in the region and is ascribed to uplift along the northeastern part of the Yellowstone hotspot between 20 and 140 ka. It is suspected that this uplift allowed the northwestern Yellowstone region to accumulate greater glacier thicknesses in the more recent past (Licciardi and Pierce, 2018; Pierce and others, 2014b).

A few of the mountain ranges in central Montana were high enough to form valley glaciers in the late Quaternary, such as the Crazy, Bridger, Spanish Peaks, Madison, Big Belt, and Elkhorn (figs. 3, 4). Few studies have been published about the Quaternary geology of these areas, other than a reconstruction of the late Pleistocene Big Timber glacier in the Crazy Mountains (Murray and Locke, 1989). This study showed that the east side of the Crazy Mountains experienced a cold/dry climate during the LGM. The Big Timber Creek glacier had an equilibrium line altitude of about 2,204 m (7,350 ft). Although the Big Snowy Mountains in central Montana have topography similar to cirque glaciers, the mountains were not sufficiently high to have accumulated glacial ice during previous glacial periods (Reeves, 1930; Porter and others, 1996). These workers ascribed the bowl-shaped geometry of the high valleys in the Big Snowy Mountains to differential erosion of resistant carbonates overlying less resistant strata.

Ice- or moraine-dammed lakes were common features of retreating glaciers in mountainous areas as tributary valleys, although only a few have been described in detail, such as where Slough Creek dammed the Lamar River of Yellowstone (Pierce, 1979; Pierce and others, 2014b; Licciardi and Pierce, 2018).

### 7.3 Eolian Deposits

Eolian silt similar to the Oahe Formation in North Dakota (Clayton and others, 1976) forms the surficial sediments on uplands along the Yellowstone River Valley of eastern Montana. These windblown silt deposits are Late Wisconsin to Recent age. They are characterized by dark A horizons in paleosols formed during times of little or no deposition interbedded with light-colored silt formed during times of accumulation. A mammoth recovered in upland silts in the South Fork Deer Creek drainage west of Glendive is buried by a dark paleosol and has been correlated with the Aggie Brown Member of the Oahe Formation (Hill, 2006; Hill and Davis, 2014). A composite buried soil developed in the upland silts south of the Yellowstone at OTL Ridge, with radiocarbon ages ranging from 13,260 to 11,760 cal yr BP (11,415 to 9,330 $^{14}$C yr BP), also may be the local equivalent of the regional Leonard Paleosol or Brady buried soil elsewhere in the Great Plains (Hill, 2006; Hill and Davis, 2014). In the Holocene, slopes were stable during relatively cool, moist periods associated with dense vegetation and were unstable during warm, dry periods when sparse vegetation covered the hillslopes (Clayton and others, 1976). Thus, these localities provide information of biogeographic patterns in this region of Montana during the late Pleistocene and early Holocene.

### 7.4 Alluvial Deposits and Landforms

Pliocene to Holocene fluvial deposits in unglaciated parts of eastern Montana are on distinct low-gradient surfaces that represent downcutting histories, stream capture, and tectonics eastward from the Beartooth Mountains to the Black Hills of South Dakota (Reheis and others, 1991; Wayne and others, 1991). Major drainages in the region, the Yellowstone, Clarks Fork Yellowstone, Bighorn, Tongue, Powder, and Little Missouri Rivers, each recorded downcutting and lateral planation histories as expressed in stream terraces. The ancestral Clarks Fork Yellowstone and Shoshone Rivers between the Beartooth and Pryor Mountains represent drainage rearrangements throughout the Quaternary from prior to the ~640 ka Lava Creek tephra to the Holocene (Ritter, 1967; Reheis and

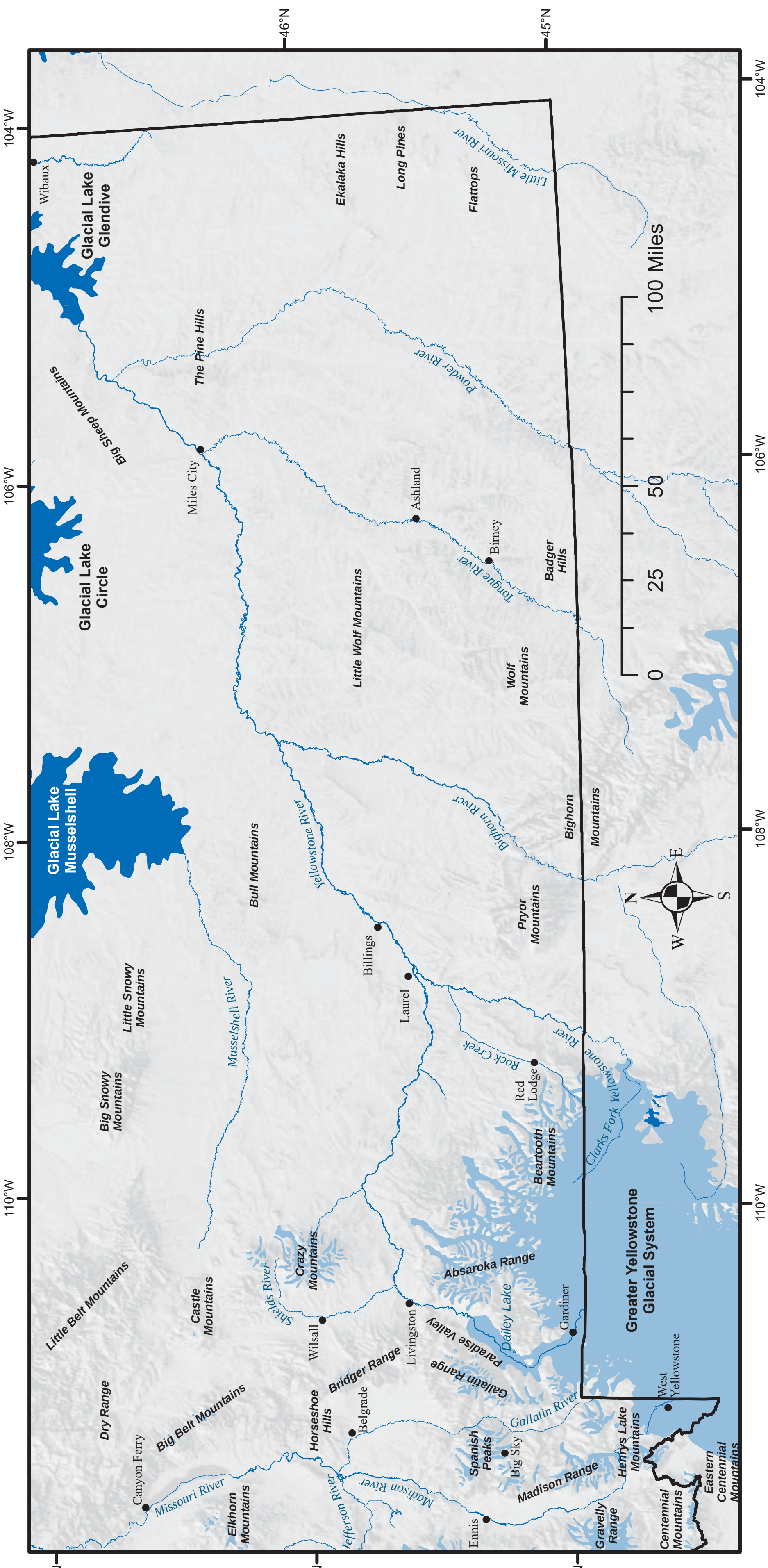


Figure 21. Southern and southeastern Montana glacial extents and features mentioned in the text.

others, 1991; Pierce and others, 2014b).

South of Billings, an outcrop of the 2.1 Ma Huckleberry ash with fist-size pumice fragments is on a terrace about 325 m (760 ft) above the Clarks Fork Yellowstone River (Izett and Wilcox, 1982). It postdates the abandonment of the drainage of the Bighorn Basin through Pryor Gap (Pierce and Reheis, 1990).

Seven regional terraces of Rock Creek and the lower Clarks Fork Yellowstone River in the Red Lodge to Laurel, Montana area record fluvial deposition and incision. The Huckleberry ash, the Lava Creek A and B, and moraines of the Pinedale and Bull Lake glaciations provide age control on the terraces (Ritter, 1967; Reheis, 1985, 1987; Blazey and Strasser, 2011). Polecat gap was occupied by the Clarks Fork Yellowstone River when the 2.1 Ma Huckleberry tuff was emplaced and deposited on the high surface, “The Mesa,” about 250 m (820 ft) above local base level (Ritter, 1967; Reheis, 1984, 1985; Reheis and others, 1991).

Distinctive, discontinuous terraces formed along the Yellowstone River and its tributaries from Wyoming to the river’s confluence with the Missouri River in northeastern Montana. Bond (1994) described five terrace levels along river valleys south and east of the Beartooth Mountains. He observed that the highest terraces represented more northeasterly transport that evolved to more northerly directions.

Streams flowing north from the Bighorn Mountains, including the Clarks Fork Yellowstone, Bighorn, Tongue, Powder, and Little Missouri Rivers, developed in pre-Quaternary times. Knowledge of the deposits’ fluvial histories and terrace levels were summarized up to 1990 by Reheis and others (1991) and are reviewed and updated here. The Beartooth, Bighorn (south of the Pryor Range), and Absaroka Mountains were glaciated in Wyoming during the Pleistocene, affecting the sediment load in the headwaters of the Clarks Fork and the Bighorn Rivers, and some of their tributaries (fig. 22). Streams established in the fine-grained sediments of the basins have lower gradients than those draining alpine areas in mountains and have therefore captured some of the steep-gradient streams (Kellogg and Vuke, 1996). During regional downcutting they established courses across parts of the Bighorn Mountains in Wyoming, cutting local bedrock canyons, analogous to the canyon downstream from the Willow Creek Reservoir in the Madison River drainage to the west (Alden, 1932; Leopold and Miller, 1954; Wayne and others, 1991).

The Quaternary fluvial history of the Powder River and its tributaries in Montana has been described in regional overviews (Leopold and Miller, 1954). The lower three terraces along the Powder River and its major tributaries are of consistent heights above base level, and are thought to have been controlled by late Pleistocene to Holocene climates (Riihimaki and others, 2009).

### 7.5 Hillslope Deposits and Landforms

Geologic mapping has documented landslides, topples, rock fall debris, and rock fall potential in the Billings area (fig. 23; Lopez, 2002; Lopez and Sims, 2003a,b). In southern and eastern Montana, unstable slopes flank river and stream valleys, especially in areas where Cretaceous or Paleocene deposits are present. The Yankee Jim landslide downstream from Gardiner dammed the Yellowstone River long enough to form a lake dated at about 12 ka (Pierce and others, 2014b). Failure of the landslide dam resulted in flood-deposited bedforms along the Yellowstone near the southern end of the Paradise Valley (Pierce and others, 2014b). Debuttressing of hillsides during deglaciation in the Gardiner area is one factor ascribed to extensive landslides near the northern entrance to Yellowstone National Park (Nicholas and others, 2017; Nicholas, 2018; Pierce and others, 2014b).

Landslides in the Big Sky area of the Madison Range have affected infrastructure for decades. A detailed map of the landslides showed that locally 100% of the landscape is made up of landslide material (Vuke, 2013).

Fire-related erosion and sedimentation along hillsides and valleys have great impacts in western North American conifer forests. The sites of one of the earliest studies were the areas burned in the 1988 Yellowstone fires. The production of extensive charcoal during both high-intensity and low-intensity fires allows for radiocarbon age control on deposits of alluvial fans and slope failures. Results from the Yellowstone region show that fire-related deposits make up about 30% of the late-Holocene alluvial fans, which recorded early, mid, and late Holocene periods of intense fire activity. Fire records also indicate climatic control on fire activity, sedimentation, and incision over millennial time scales (Meyer and others, 1995).

Natural burning of coalbeds in the Paleocene Fort Union Formation has thermally metamorphosed and

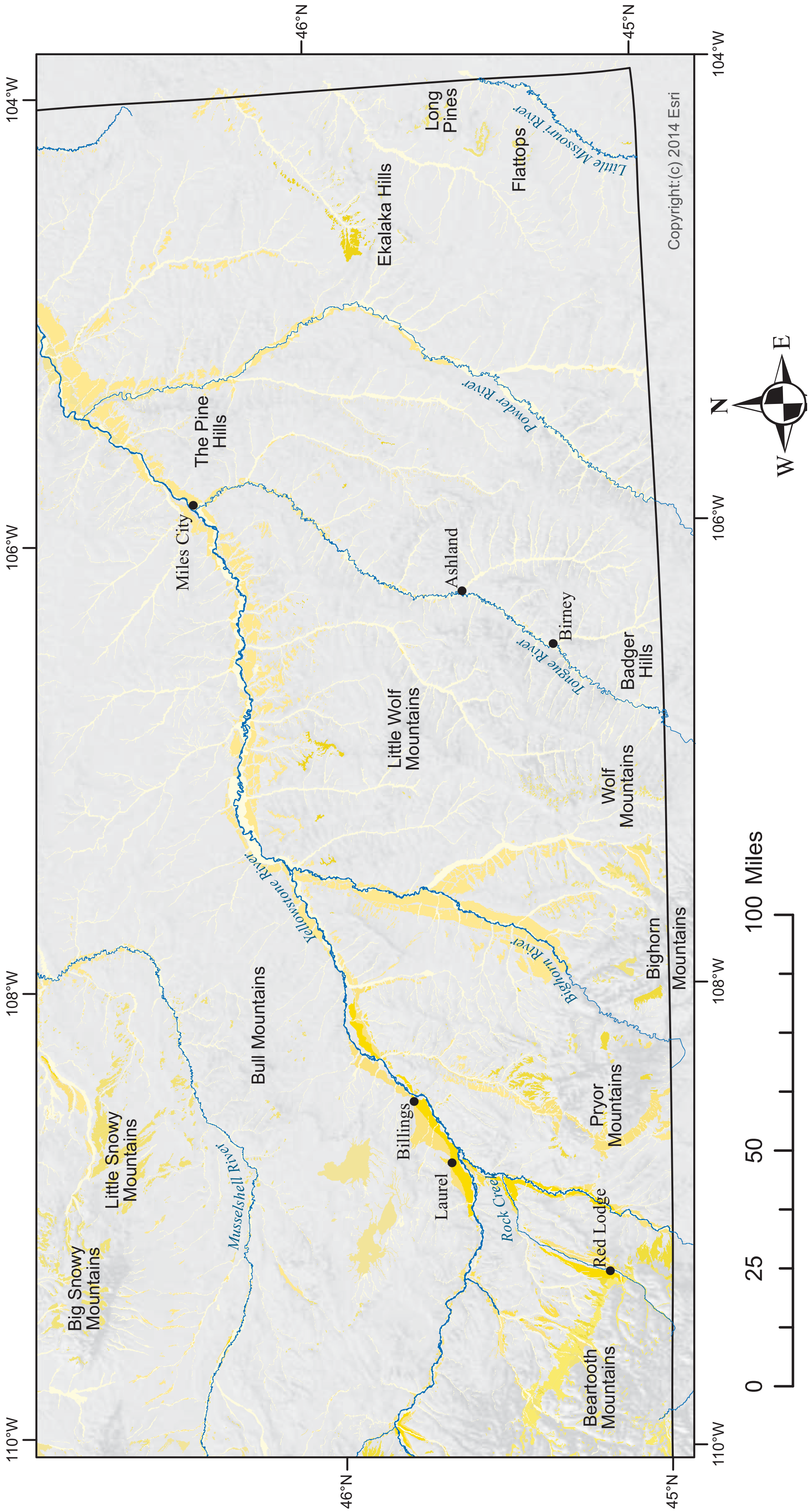


Figure 22. Streams and alluvial deposits (yellow) of south and southeastern Montana.


Figure 23. Blocks of the Eagle Sandstone that have toppled or slid off of the Rimrocks north and southeast of Billings during historic times (from Lopez and Sims, 2003b). (A) This rock fall occurred near the intersection of 6th Ave North and Main Street in September 1994. (B) This rock fall occurred in fall 2001. After toppling from the cliff, the boulder traveled about 1,000 ft down the slope. (C and D) These photographs illustrate the proximity of the rock-fall hazard area to housing developments in the Billings Rimrocks area.

hardened overlying clay-rich sandstone and siltstone beds. These predominantly reddish beds are known as clinker. Ignition and significant burning of the coal preferentially happens on dry sites and during times of higher aridity (Heffern and others, 2007). Clinker preferentially resists erosion because of its increased hardness and its high water infiltration capacity through the production of fracture networks, which leads to clinker as recharge zones for groundwater and the lack of rill erosion of the slopes. Thus, clinker typically caps ridges, knobs, and buttes above the less resistant, unmetamorphosed Fort Union Formation.

Through fission-track dating of zircons and (U-Th)/He in baked sandstones, clinker has been used for determining erosion rates of landscapes in Montana and Wyoming. Riihimaki and Reiners (2012) reported that ages from the Knobloch coal zones in the Tongue River Valley near Ashland, and Birney, Montana range from 1.1 Ma to 10 ka. These data along with additional samples in Wyoming show that clinker in basins away from mountain fronts preferentially formed during times of high eccentricity of Earth's orbit. This may indicate that increased seasonality and solar insolation encouraged clinker formation more than interglacial climates (Riihimaki and others, 2009; Riihimaki and Reiners, 2012). These intervals of increased coal burning and clinker formation are thought to be times of increased downcutting in the Powder River Basin. The downcutting may have been due to increased seasonality and intensity of convective storms bringing lightning and monsoon events, along with increased snowfall and spring runoff (Coates and Naeser, 1984).

### 7.6 Pleistocene Mammal Localities

The central and eastern region of northern Montana encompassing parts of the drainage of the Missouri River also contains Pleistocene deposits with mammal fossils. As an example, within the Milk River Basin, gravel pits in the vicinity of Havre and Malta include faunal remains (Pecora and others, 1957; Davis, 1975, 1986; Fullerton and Colton, 1986; Fullerton and others, 2012). These finds are often associated with Pleistocene terrace gravels (Pecora and others, 1957). *Mammuthus, Equus*, and *Camelops* have been recovered in alluvial deposits underlying a middle Pleistocene till at Havre. For example, in the reference section for the Fort Assiniboin, Herron, and Havre tills exposed at north Havre, there are Irvingtonian vertebrate fossils in the basal gravels (Fullerton and others, 2012). Remains of *Mammuthus* were recovered from possible glacial outwash gravels in the Saco–Hinsdale area (Davis, 1975, 1986). South of Havre, fossils are present in gravels northeast of Roy that are overlain by Illinoian age till and younger lake sediments (Hill, 2006). Fluvial deposits in the Gallatin Valley (at the JTL gravel pit near Belgrade, and along the East Gallatin River; fig. 21) contain remains of *Mammuthus* (Hill, 2006).

North of the Fort Peck Reservoir, remains of *Mammuthus* and *Equus* have been found in gravels near Glasgow, Nashua, and Frazer (Jensen and Varnes, 1964; Hill, 2006). Fossils attributed to "*Mammuthus boreus* Hay (*Mammuthus primigenius* Blumenbach–*Parelephas jeffersoni* Osborne)" were collected from the Wiota gravels at Tiger Butte (Jensen and Varnes, 1964). The taxonomic identification of the specimen as *Mammuthus primigenius* might imply that part of the Wiota gravels are Upper Pleistocene (Enk and others, 2016; Lister and Sher, 2015). Remains of *Mammuthus* and *Equus* from south of Frazer were found in gravel overlain by a till (Jensen and Varnes, 1964). South of the Fort Peck Reservoir, fossils of *Bison occidentalis* have been recovered from gravel deposits (Rasmussen, 1974a), and a possible *B. latifrons* has been reported from near Lisk Creek and radiocarbon dated to 24,220–23,750 cal yr BP (19,930 ± 70 $^{14}$C yr BP; Melton and Davis, 1999). Also south of Fort Peck, near Box Creek, a faunal assemblage containing Mammuthus provides an age of 38,420–36,560 cal yr BP (33,280 ± 320 $^{14}$C yr BP; Beta-155639; Hill, 2006). Remains of *Mammuthus* have also been reported from the Redwater Creek area (Hay, 1924) and *Ovibos moschatus* is known from near Outlook (Neas, 1990).

Within the Yellowstone River Basin, extending over the south-central and southeastern regions of Montana, there are several known Pleistocene faunal localities. Fossils have been reported from the Shields River area (north of Livingston), in the Pryor Mountain region (south of Billings); the valleys of northeastward-flowing tributaries of the Yellowstone River such as the Tongue and Powder Rivers and Beaver Creek; southeastward-flowing streams such as South Fork Deer Creek; and terrace deposits along the Yellowstone River Valley itself. Several occurrences of *Mammuthus* have been reported from the Livingston area, including the possible mammoth foreshafts associated with Clovis artifacts near Wilsall (Taylor, 1969; Lahren and Bonnichsen, 1974; Jones and Bonnichsen, 1994; Stafford, 1999; Owsley and Hunt, 2001; Becerra-Valdivia and others, 2018).

In the Pryor Mountains, south of Billings, Pleistocene mammals have been recovered from False Cougar Cave and Shield Trap Cave (Bonnichsen and others, 1986; Graham and others, 1987). The lowest stratum at False Cougar Cave rests on bedrock and is interpreted as a cut-and fill sequence of fluvial deposits (Bonnichsen and others, 1986). Late Pleistocene small mammal remains were found in these deposits and there are late Pleistocene radiocarbon dates from 18,490–16,970 cal yr BP and 12,720–12,020 cal yr BP (14,590 ± 300 and 10,530 ± 140 $^{14}$C yr BP). The lowest depositional unit at Shield Trap Cave also contains a late Pleistocene or early Holocene faunal assemblage, and other deposits are dated to about 10,440 cal yr BP (9,230 $^{14}$C yr BP; Bonnichsen and others, 1986; Graham and others, 1987).

The stream valleys south of the Yellowstone River contain fossils of *Mammuthus* and *Bison*. For example, fossils have been recovered within the Tongue River Valley (Winchell, 1882; Hay, 1924; Bass, 1932; Melton and Davis, 1999), the Powder River Valley (Hay, 1924; Hill, 2006), the Beaver Creek Valley near Wibaux (Hill, 2006), and near Humboldt Creek within the Little Missouri River Basin (Frison, 1996). *Bison antiquus* or possibly *B. occidentalis* fossils from the Tongue River area date to 11,000–10,610 cal yr BP (9,510 ± 60 $^{14}$C yr BP; Beta-122117; Melton and Davis, 1999), and the Mill Iron Site local fauna is associated with dates ranging from about 13,590–13,190 cal yr BP to 12,680–12,450 cal yr BP (11,570 to 10,760 $^{14}$C yr BP; Frison, 1996; Walker and Frison, 1996).

Stream valleys north of the Yellowstone River also contain Pleistocene fossils. *Mammuthus* remains have been reported from the Richey area (Madden, 1981) and also near Coal Creek, northeast of Terry (Hill, 2006). A nearly complete *M. columbi* skeleton found in the upland northeast of Lindsay, in the South Fork Deer Creek drainage (fig. 24; Davis and Wilson, 1985; Hill and Davis, 1998), appears to date to older than 14,000 cal yr BP (12,000 $^{14}$C yr BP), based on a set of AMS $^{14}$C measurements (Hill, 2012; Hill and Davis, 2014). In this upland area north of the Yellowstone River, the Tertiary bedrock is overlain by loess deposits containing buried soils. The mammoth remains were found in the silts and under a buried paleosol (Hill, 2012).

Along the Yellowstone River, Pleistocene fossils were found in gravels and have assisted in constraining the age of the Yellowstone terraces (fig. 25). A pre-Wisconsin (Sangamon?/Illinoian?) faunal assemblage from the terrace gravels north of Miles City (Wilson and Hill, 2000; Hill, 2006) includes *Megalonyx jeffersonii, Paramylodon (Glossotherium) harlani, Mammuthus columbi, Mammut americanus, Equus, Arctodus simus, Camelops*, and *Bootherium (Symbos)*. West of Miles City, proboscidean (cf. *Mammuthus*) fossils have been collected from the Paragon gravel pit, and fossils referred to *Symbos* have been found in gravels east of the town (McDonald and Ray, 1989). Several finds of *Mammuthus* have been reported from gravel pits at Glendive. At the Crisafulli pit, the gravels forming the 12–15 m terrace contain *Mammuthus* and are overlain by silts (Hill, 2006). Collagen from a mammoth tooth from the Crisafulli pit provided an age of 24,980–24,330 cal yr BP (20,470 ± 80 $^{14}$C yr BP; Beta-155642). The age of the mammoth tooth found in gravels underlying what has been interpreted as Glacial Lake Glendive silts at Glendive was used to provide a maximum age for the late Wisconsin Crazy Horse till (Fullerton and others, 2016).

Figure 24. Buried soil in silt deposits (loess) correlated with the Oahe Formation of Clayton and others (1976); Mammoth fossils excavated from below the A-horizon of the paleosol are dated to about 14,400 cal yr BP (12,300 $^{14}$C yr BP; Hill and Davis, 2014). Excavations exposed eolian silts within the Deer Creek drainage, near Lindsay, in eastern Montana.

## 8. OUTSTANDING QUESTIONS AND SUGGESTIONS FOR FUTURE WORK

Although the glacial and other Quaternary deposits and landforms have attracted geological research for over 100 years in Montana, many key questions still need further work in order to understand the history. Some of the unanswered topics are:

- Resolving the different interpretations of continental glacial deposits in the eastern part of the State. Description and mapping of till sheets

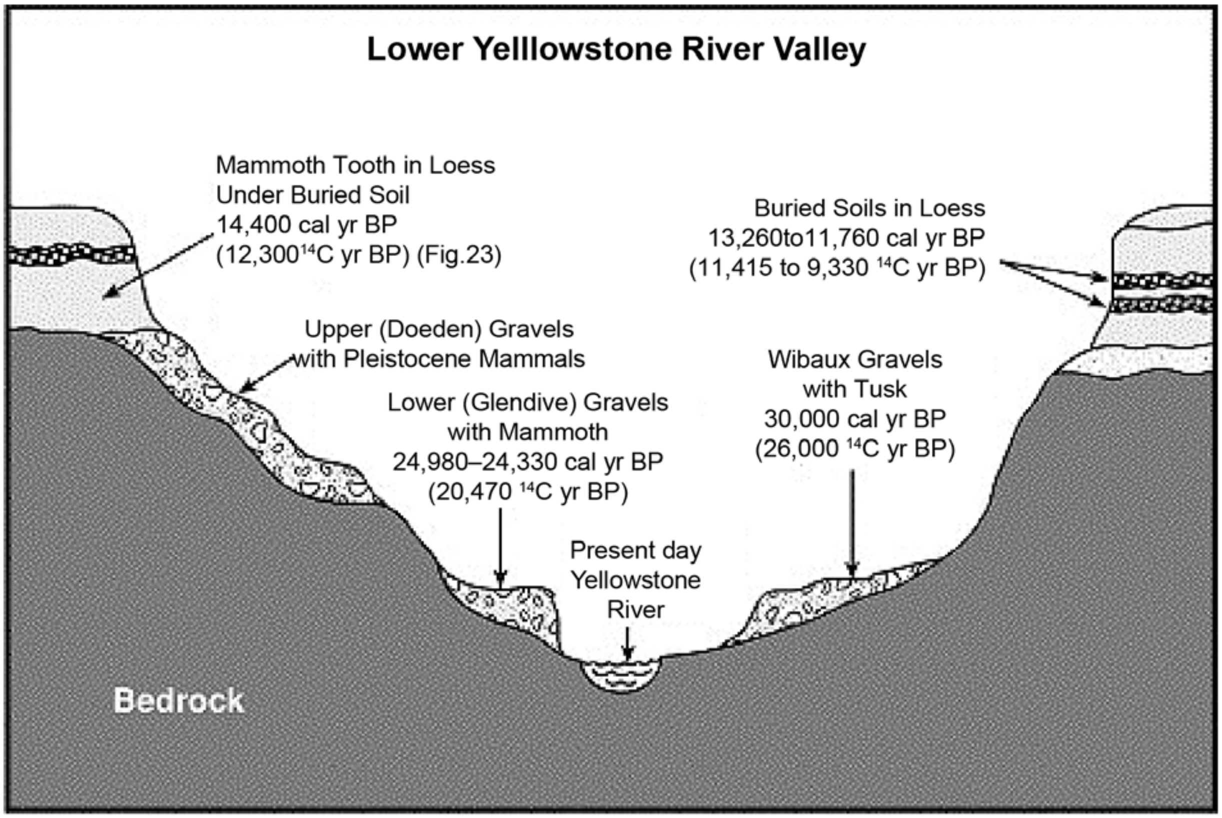


Figure 25. Schematic cross section of the lower Yellowstone River Valley showing terraces and associated vertebrate localities. The lower gravels (Glendive and Wibaux gravels) are dated to 24–30,000 cal yr BP (20–26,000 $^{14}$C yr BP). The upland silts with buried soils are of late Pleistocene or early Holocene age and can be correlated with the Oahe Formation loess of North Dakota (from Hill, 2006).

has led some workers for decades to differentiate tills as representing multiple advances of Laurentide (or Keewatin) ice into the State during MIS 2, 6, and possibly older ages. However, work in Alberta and Saskatchewan has argued that pre-MIS 2 advance of ice into Alberta, and across the border into the USA, did not happen. Additional stratigraphic work across the international border and geochronology would help resolve this contradiction.

- Relative and absolute dating of mountain and piedmont glacial deposits, glacial lake deposits, and alluvium is needed along most of the western Montana mountain fronts. Differentiating stages of glaciation during each glacial period has started in some of the western USA mountain glacier deposits. Comprehensive description and mapping of these deposits with soils and relative weathering parameters would be a good first step in developing a statewide chronology of glaciation.
- Correlation of alluvial deposits in intermontane valleys and their tributaries to glacial deposits of different ages has proved useful in understanding the climatic controls on alluvial sedimentation in the Madison River Valley, and could be expanded elsewhere.
- Something barely touched on here is the distribution of periglacial deposits and landforms, because no regional work has been done on this subject. Comprehensive mapping and dating of these sediments would expand our knowledge of the glacial climate.
- Regional mapping of landslides, especially if high-resolution topography data become available, would have great use in prediction of the distribution and triggering mechanisms of landslide failures in mountains and valleys.
- Asymmetric hillslopes are common in much of Montana, but have been little studied. Some of these hillslopes lead to topography that has been interpreted as tectonically rotated blocks, but further work showed no fault offsets. Therefore, the erosional processes, controls on sediment production, and sediment yield to streams are not uniform in landscapes.

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# APPENDIX A

# LIST OF PLEISTOCENE MAMMALS IN MONTANA

## Appendix A

(A) List of Pleistocene mammals from Montana: large to medium size. Locations for each taxon are indicated.

XENARTHRA

Megalonychidae

*Megalonyx jeffersonii* (Jefferson's ground sloth)

Doeden

Mylodontidae

*Paramylodon (Glossotherium) harlani* (Harlan's ground sloth)

Doeden

CARNIVORA

Canidae

*Canis dirus* (dire wolf)

Orr Cave

*Canis latrans* (coyote)

Blacktail Cave

Merrell

*Canis lupus* (gray wolf)

Blacktail Cave

Merrell

*Canis/Vulpes*

False Cougar Cave (unit II)

*Vulpes* sp.

Blacktail Cave

False Cougar Cave (units II and III)

Felidae

Acinonychinae

*Miracinonyx (Acinonys) trumani* (American cheetah)

Sheep Rock Spring

Felinae

*Lynx rufus* (bobcat)

Clark Fork Locality No. 9

Marchairdontinae

*Homotherium serum* (Scimitar cat)

Merrell

Mustelidae

*Gulo gulo* (wolverine)

Blacktail Cave

*Mustela* sp.

Shield Trap

*Mustela frenata* (long-tailed weasel)

Clark Fork Locality No. 13

False Cougar Cave (unit II)

*Mustela nigripes* (black-footed ferret)

Orr Cave

*Mustela erminea/nivalis* (ermine/least weasel)

False Cougar Cave (unit II)

*Taxidea taxus* (badger)

Blacktail Cave

False Cougar Cave (unit II)

Ursidae

Blacktail Cave

*Arctodus simus* (giant short-faced bear)

Doeden

*Ursus* sp.

Merrell

PROBOSCIDEA

Proboscidea localities

Deer Lodge Gompotherid “Trilophodon” Mastodon

Cascade Area

Clark Fork Locality No. 3

Elephantidae

*Mammuthus* sp. (mammoth)

Helena Area

Stein Ranch

Mill Iron (cf. *Mammuthus* sp.)

Glendive-Crisafulli Gravels

*Mammuthus imperator* (imperial mammoth)

Spokane Bar/Sponambar (*Elephas columbi*?, *E. imperator*, *M. [Parelephas] imperator*)

*Mammuthus columbi* (Columbian mammoth)

Red Water Creek/Axtell

Glendive Canal

Powder River, Kimball/Hocketts (*Elephas columbi* or possibly *E. imperator*)

Tongue River, Ashland

Rosebud

Diamond City

Virginia City

Helena-Wahburn Expedition

Merrell

Sun River Canyon

Havre Area Gravels

Lindsay, South Fork of Deer Creek

Box Creek

Richey Area

Missouri River (*M. columbi jeffersonii* in Dudley, 1988).

*Mammuthus primigenius* (northern/siberian wooly mammoth)

Wiota Gravels-Frazer

Wiota Gravels-Tiger Butte (also designated *M. boreus*, *Paraelephas jeffersoni*)

Mammutidae

*Mammut americanum* (American mastodon)

Doeden

Pryor Creek

Diamond City

Gallatin Canyon

PERISSODACTYLA

Equidae

*Equus* sp. (horse)

Lovejoy area

Sheep Rock Spring

Rock Creek

Merrell

Clark Fork Locality No. 6

Clark Fork Locality No. 7

Clark Fork Locality No. 8

False Cougar Cave (unit II)

Doeden

*Equus simplicidens proversus*

Clark Fork Locality No. 2 (*E. proversus)*

*Equus* cf. *conversidens* (Mexican horse)

Blacktail Cave

Havre Area Gravels (*E. conversidens calobatus*)

*Equus exelsus*

Havre Area Gravels

ARTIODACTYLA

Artiodactyl

Camelidae

Flaxville Area

*Camelops* sp. (camel)

Sheep Rock Spring

Clark Fork Locality No. 6

Clark Fork Locality No. 8

Merrell (*C.* cf. *hesternus*)

False Cougar Cave (unit II)

Doeden

?*Camelops minidokae*

Havre Area Gravels

Cervidae

*Odocoilheus* sp. (Nearctic deer)

Merrell

*Rangifer tarandus* (caribou)

Clark Fork Locality 11

Antlocapridae

*Antilocapra* sp. (pronghorn)

Blacktail Cave

Merrell (cf. *A. americana*)

Bovidae

*Bison* sp. (bison)

Merrell

Clark Fork Locality No. 11

Indian Creek

*Bison alaskensis*

Collection at Canyon, Texas

*Bison latifrons* (giant long-horned bison)

List Creek (*B*. cf. *latifrons*)

Merrell (*B*. cf. *latifrons*)

Doeden (*B*.cf. *latifrons*)

*Bison antiquus*

Mill Iron (*B*. cf. *antiquus*)

Indian Creek (*B*. cf. *antiquus*)

Sheep Rock Spring (*B*. cf. *antiquus*)

MacHaffie (*B*. cf. *antiquus*)

Upper Holter Lake (*B*. cf. *antiquus*)

*Bison occidentalis*

Madigan Gulch

Blacktail Cave

Tongue River area (*B*. cf. *occidentalis/antiquus)*

*Bison bison* or *Bison* cf. *bison*

Clark Fork Locality No. 5

Clark Fork Locality No. 9

Clark Fork Loacilty No. 10

False Cougar Cave (unit II)

*Bootherium* or *Symbos* (muskox)

Blacktail Cave

Payes

Doeden

*Ovibos moschatus* (barren-ground/tundra muskox)

Outlook

*Ovis canadensis* (bighorn/mountain sheep)

Sheep Rock Spring

Indian Creek

False Cougar Cave (units II and III)

(B) List of Pleistocene mammals from Montana: small to medium size. Locations for each taxon are indicated.

INSECTIVORA

Soricidae

*Sorex cinereus* (masked shrew)

False Cougar Cave (units III and II)

Shield Trap (stratum IV)

*Sorex nanus* (dwarf shrew)

Shield Trap (stratum IV)

*Sorex monticolus* (vagrant shrew)

False Cougar Cave (unit II)

*Sorex monticolus/merriami* (vagrant/Merriam's shrew)

False Cougar Cave (unit II)

*Sorex merriami* (Merriam's shrew)

Shield Trap (stratum IV)

RODENTIA

Sciuridae

*Cynomys* sp. (Prarie dog)

Blacktail Cave

*Cynomys leucurus* (white-tailed prairie dog)

Clark Fork Locality No. 3 (*C. ludovicianus*, Rasmussen, 1974b)

Clark Fork Locality No. 7 (*C. ludovicianus*, Rasmussen, 1974b)

Clark Fork Locality No. 12 (*C. ludovicianus*, Rasmussen, 1974b)

Hoover Creek MV8702

*Cynomys ludovicianus* (black-tailed prairie dog)

Indian Creek

*Marmota* sp. (marmot)

Indian Creek

Blacktail Cave

*Marmota caligata* (hoary marmot)

Blacktail Cave

*Marmota flaviventris* (yellow-bellied marmot)

False Cougar Cave (units II and III)

Shield Trap (stratum IV)

Clark Fork No. 13

Blacktail Cave

Indian Creek

*Spermophilus* sp. (ground squirrel)

Blacktail Cave

Merrell

Centennial Valley (*Citellus* in Honkala, 1949)

*Spermophilus cf. columbianus* (Columbian ground squirrel)

Clark Fork Locality No. 6

*Spermophilus richardsonii* (Richardson's ground squirrel)

False Cougar Cave (units II and III)

Clark Fork No. 13

*Spermophilis tridecemlineatus* (thirteen-lined ground squirrel)

False Cougar Cave (units II and III)

Mill Iron (*S.* cf. *tridecemlineatus* )

*Spermophilus variegatus* (rock squirrel)

False Cougar Cave (unit III)

*Spermophilus variegatus* (rock squirrel)

False Cougar Cave (unit III)

*Spermophilus lateralis* (golden-mantled ground squirrel)

False Cougar Cave (units II and III)

*Tamias minimus* (least chipmunk)

False Cougar Cave (unit II)

Shield Trap (stratum IV)

*Tamiasciurus hudsonicus* (red squirrel)

False Cougar Cave (units II and III)

Shield Trap (stratum IV)

Castoridae

*Castor californicus*

Clark Fork Locality No. 1

*Castor canadensis* (beaver/Canadian beaver)

Merrell

Blacktail Cave

Geomyidae

*Thomomys* sp. (pocket gopher)

Blacktail Cave

*Thomomys talpoides* (northern pocket gopher)

Clark Fork Locality No. 4

Clark Fork Locality No. 6 (Hoover Creek local fauna)

Clark Fork Locality No. 13

False Cougar Cave (units II and III)

Shield Trap (stratum IV)

Mill Iron

Centennial Valley (Honkala-Hibbard)

Muridae

Arvicolinae

*Clethrionomys* sp. (red-backed mouse)

False Cougar Cave (units II and III)

*Dicrostonyx torguatus* (collared lemming)

False Cougar Cave (units II and III)

*Lemmiscus (Lagurus) curtatus* (sagebrush vole)

False Cougar Cave (units II and III)

Clark Fork Locality No. 13

Merrell

*Microtus* sp. (vole)

Blacktail Cave

Indian Creek

Clark Fork Locality No. 6

*Microtus longicaudus* (long-tailed vole)

Mill Iron

*Microtus longicaudus/montanus* (long-tailed/montane vole)

False Cougar Cave (units II and III)

*Microtus* cf. *pennsylvanicus* (meadow vole)

Clark Fork Locality No. 13

Shield Trap (stratum IV)

*Microtus richardsonii* (water vole)

Clark Fork Locality No. 13 (*Arvicola richardsonii*, Rasmussen, 1974b)

*Microtus ochrogaster* (prairie vole)

Mill Iron

*Phenacomys (paraphenacomys) alpipes* (white-footed vole)

Blacktail Cave

*Phenacomys intermedius* (heather vole)

False Cougar Cave (units II and III)

*Ondatra zibithicus* (muskrat)

Clark Fork Locality No. 13

Merrell

Sigmodontinae

*Neotoma* sp.

Blacktail Cave

*Neotoma cinera* (brushy-tailed wood rat)

False Cougar Cave (units II and III)

Blacktail Cave (*N.* cf. *cinera*)

*Peromyscus maniculatus* (deer mouse)

False Cougar Cave (units II and III)

Shield Trap (stratum IV)

Clark Fork Locality No. 6 (*P.* cf. *maniculatus*)

Clark Fork Locality No. 13 (*P.* cf. *maniculatus*)

Mill Iron (*P.* cf. *maniculatus*)

Erethizontidae

*Erethizon dorsatum* (porcupine)

False Cougar Cave (unit II)

LAGOMORPHA

Ochontonidae

*Ochotona princeps* (pika)

False Cougar Cave (units II and III)

Leporidae

*Lepus* sp.

Clark Fork Locality No. 6

Blacktail Cave

False Cougar Cave (units II and III)

Shield Trap (stratum IV)

*Sylvilgagus* sp. (cottontail rabbit)

Indian Creek

False Cougar Cave (units II and III)

*Sylvilagus nuttallii* (Nuttall's cottontail)

Clark Fork Locality No. 9