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Stratigraphic evidence for multiple drainings of glacial Lake Missoula along the Clark Fork River, Montana, USA

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Abstract

Glacial Lake Missoula, a source of Channeled Scabland flood waters, inundated valleys of northwest Montana to altitudes of ~1265 m and to depths of >600 m, as evidenced by shorelines and silty lacustrine deposits. This study describes previously unrecognized catastrophic lake-drainage deposits that lie stratigraphically beneath the glacial-lake silts. The unconsolidated gravelly flood alluvium contains imbricated boulder-sized clasts, cross-stratified gravel with slip-face heights of 2–>35 m, and 70- to 100-m-high gravel bars which all indicate a high-energy, high-volume alluvial environment. Gravel bars and high scablands were formed by catastrophic draining of one or possibly more early, high lake stands (1200–1265 m). Most glacial-lake silt, such as the Ninemile section, was deposited stratigraphically above the earlier deposits, represents a lower lake stand(s) (1050–1150 m), and was not deposited in lake(s) responsible for the highest discharge events. The glaciolacustrine silt-covered benches are incised by relict networks of valleys formed during the drainage of the last glacial lake. Significant erosion associated with the last lake draining was confined to the inner Clark Fork River canyon.

Keywords: Catastrophic floods; Channeled Scabland; Glacial Lake Missoula; Late Pleistocene; Ninemile section

Introduction

The drainage history of glacial Lake Missoula is mostly known by sedimentologic, stratigraphic, and geomorphic analysis of deposits and landforms outside the lake basin, principally from northern Idaho and the Channeled Scablands of Washington (Fig. 1) (Bretz, 1969; Baker, 1973; Waitt, 1980, 1985; O'Connor and Baker, 1992; Benito and O'Connor, 2003; Clague et al., 2003). Evidence within the lake basin for high-energy drainage of glacial Lake Missoula includes 5- to 15-m-high dunes on Camas Prairie, scabland erosion, and eddy bars along the Flathead River, its tributaries, and the lower Clark Fork River canyon (Pardee, 1942; Chambers, 1984).

Evidence within the lake basin used for arguing that the lake drained multiple times consists mostly of a few sections of rhythmically bedded glaciolacustrine sand, silt, and clay sequences, most notably the "Ninemile section" near the confluence of Ninemile Creek and the Clark Fork River (Fig. 2). These deposits have been cited as evidence for about 40 fillings and drainings of glacial Lake Missoula (Alt and Chambers, 1970; Curry, 1977; Waitt, 1980; Atwater et al., 2000; Booth et al., 2004). The rhythmically bedded sequence at Ninemile has been correlated to slackwater deposits in the states of Idaho, Oregon, and Washington of repeated, catastrophic Channeled Scabland floods (Waitt, 1980, 1985; Atwater et al., 2000). However, Levish (1997) found no evidence for multiple fillings and drainage in the glaciolacustrine deposits in the northern Flathead River portion of the lake basin. He disputed the interpretation that rhythmic bedding in the silty glaciolacustrine sections, such as at the Ninemile and Bison Range sections (Fig. 2), represents filling-drainage cycles. Others have described evidence for either 22 (Chambers, 1984) or eight (Fritz and Smith, 1993) major fluctuations in lake levels at the Ninemile section; however, these previous studies did not infer catastrophic drainage of the lake. Shaw et al. (1999, 2000) have suggested that the rhythmic bedding in the Ninemile section can be explained by turbidite and varve sedimentation in the glacial lake rather than by filling-drainage cycles.

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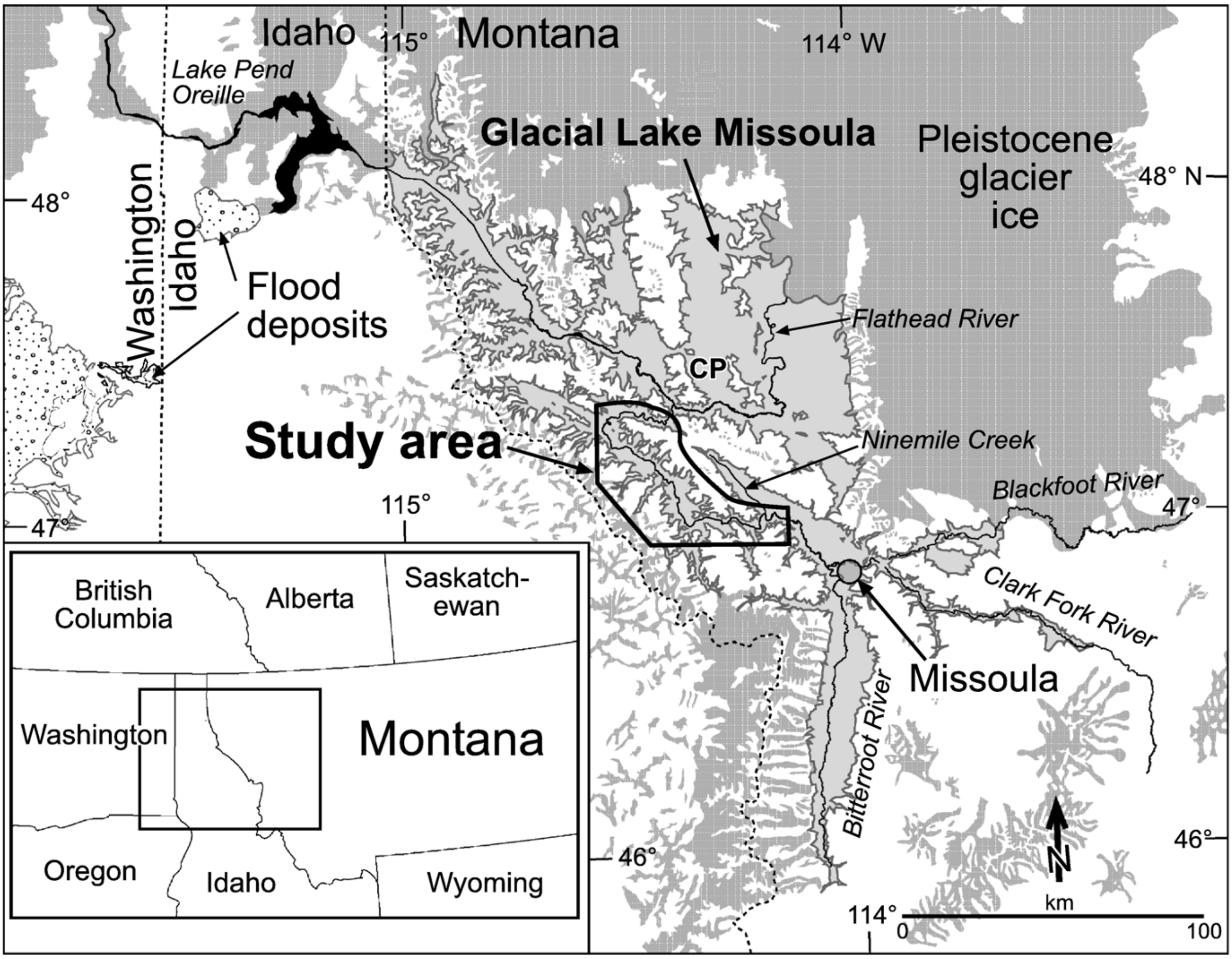

Figure 1. Location map of the study area. CP=Camas Prairie. Distribution of Pleistocene glacial ice in Montana is from Locke and Smith (2004); the ice and flood channels of the Channeled Scabland are from U.S. Forest Service (1998).

Whereas previous work has looked to the glaciolacustrine silt section for interpreting lake draining cycles, this paper discusses a larger record of glacial Lake Missoula sedimentation in the southern upper Clark Fork River basin portion of the lake basin (Fig. 1). Recent mapping of Quaternary deposits in the Clark Fork River valley has shown that the Ninemile section of silty glaciolacustrine deposits overlies catastrophic flood alluvium and represents about 20% of the glacial-lake deposits in the region (Lonn and Smith, 2005). The significance of the glaciolacustrine deposits in the history of glacial Lake Missoula and correlations of the deposits are best understood by analysis of the complete section of lake and lake-drainage deposits. The intent here is to put the silty glaciolacustrine deposits in a stratigraphic context of other evidence for drainage of glacial Lake Missoula.

The distribution, thickness, sedimentologic properties, and stratigraphic positions of deposits were mapped along the Clark Fork River. The sedimentology of gravelly deposits along the river valley is described to distinguish those deposited during drainage events from normal fluvial flows. These depositional units and erosional scabland features provide the basis for a relative chronology of glacial Lake Missoula stands and relative flood magnitudes.

Background

The Clark Fork River and its major tributaries, the Flathead, Bitterroot, and Blackfoot rivers, drain westward from the North American continental divide to Lake Pend Oreille, the site of the Pleistocene glacial dam for glacial Lake Missoula. The study area is the 100-km-long canyon reach along the Clark Fork River from upstream of its confluence with Ninemile Creek to the confluence of the Flathead River (Fig. 1). The river is on bedrock along 43% of the canyon (Lonn and McFadden, 1999; Lonn and Smith, 2005 and unpublished mapping). The incised valley floor is 0.6- to 5-km-wide and underlain by as much as 130 m of unconsolidated silt, sand, and gravel. Sources for the deposits are local bedrock, mostly lower greenschist-grade Proterozoic metasedimentary Belt Supergroup. Some weakly to moderately consolidated Tertiary siltstones, sandstones, and carbonaceous shales border the Quaternary deposits at the upstream end of the study area.

Glacial Lake Missoula

Glacial Lake Missoula was impounded behind the Purcell lobe of the Cordilleran ice sheet near Lake Pend Oreille and the

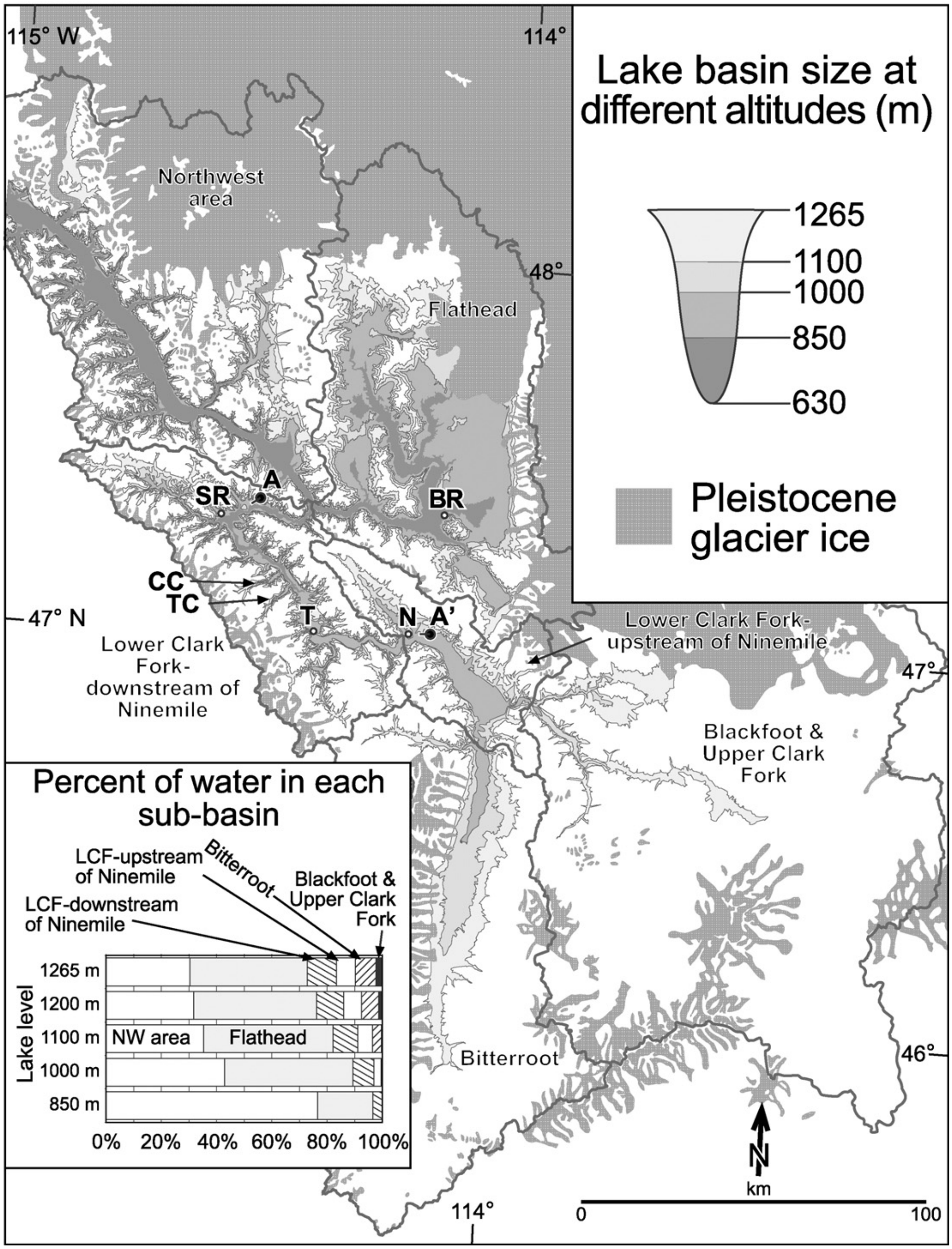

Figure 2. Map and relative volumes of subbasins of glacial Lake Missoula. Glacial lake deposits are at the Ninemile section (N) and Bison Range section (BR); A–A′ end points of cross section in Figure 6; SR = St. Regis; T = Tarkio; CC = Cedar Creek; TC = Trout Creek.

Montana/Idaho state border (Smyers and Breckenridge, 2003). The lake, first described by Pardee (1910, 1942), inundated the intermontane valleys in western Montana. It attained an altitude of at least 1265 m and possibly 1280 m; the 1265-m level is commonly taken as the maximum water level (Fig. 2) (Pardee, 1942; O'Connor and Baker, 1992; Levish, 1997). Although many shorelines range between 840 and 1150 m, a detailed chronology of lake stands has not been postulated because of the difficulty in correlating shorelines and lake deposits around the basin. This difficulty is due to the lack of published chronometric or relative dates on deposits in the basin, the lack of prominent or characteristic lake stands, and the lack of lateral continuity of shoreline deposits. Isostatic movement of deposits in the lake basin has not been interpreted because of the inability to correlate shorelines around even small parts of the basin margins. Dating of flood deposits outside the lake basin and the advance and retreat histories of the Purcell lobe currently provide the only age control for the lake deposits. Most of the radiocarbon ages on Channeled Scabland

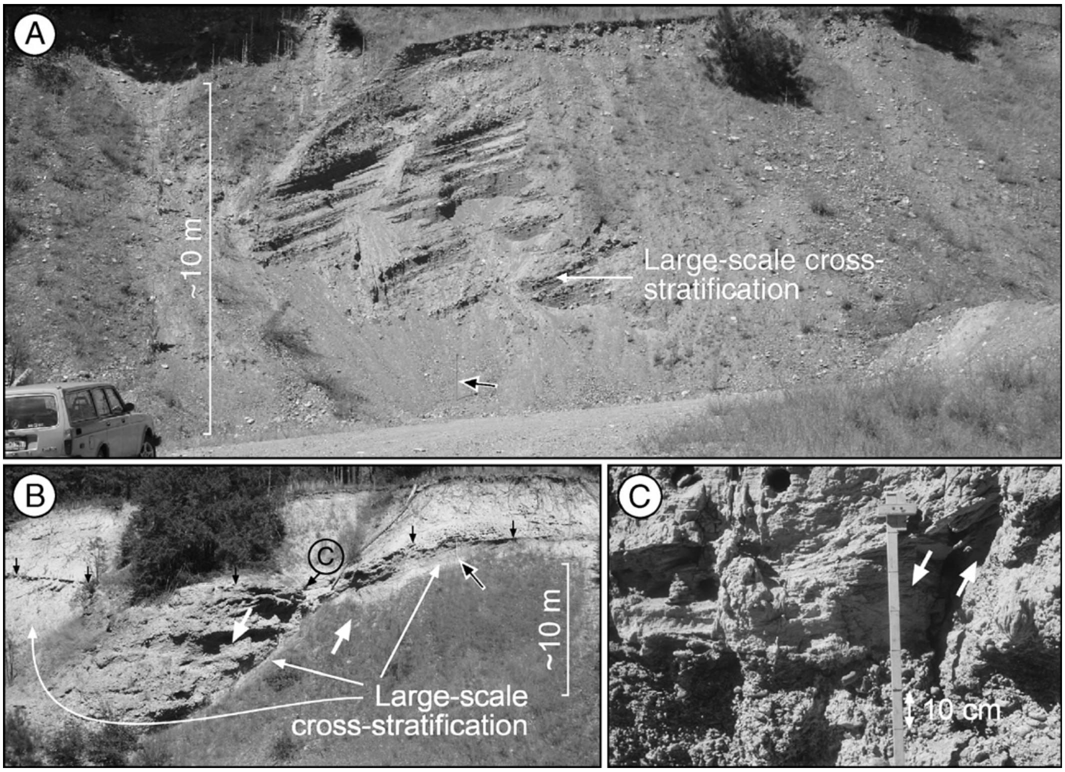

Figure 3. Exposures of gravelly alluvium. Scales are shown by 1.5-m-tall measuring staff at arrows: (A) Large-scale cross-stratification in gravel and coarse-grained sand. Location looking NW near the confluence of Trout Creek with the Clark Fork River (Fig. 2); flow was from right to left, away from the Clark Fork River, latitude 47.1402°N, longitude 114.8472°W. (B) Large-scale cross-stratification developed in granule- to boulder-sized gravel capped by Lake Missoula beds, contact at black arrows; flow was from right to left; white arrows show movement on syndepositional slump; location in Figure 5. (C) Detail of contact between gravelly alluvium and Lake Missoula beds in (B) at location of soft-sediment deformation of slump.

floods are late Wisconsin in age, between about 13,000 and 19,000 ^{14}C yr BP (Benito and O'Connor, 2003; Clague et al., 2003). Pre-Wisconsin and earlier Wisconsin floods in eastern Washington (McDonald and Busacca, 1988; Pluhar et al., 2006) suggest that glacial Lake Missoula may have been a source for flood waters before the last glacial maximum in late Wisconsin time.

The water volumes of glacial Lake Missoula were calculated from modern topography [30-m digital elevation model (DEM)]; assumed lake levels of 1265, 1100, 1000, and 850 m; and the assumed position of the Flathead lobe of the Cordilleran ice sheet at the Polson moraine (Fig. 2) (Pardee, 1942; Alden, 1953; Levish, 1997; Locke and Smith, 2004). The topography in the basin has changed during and after lake impoundment. Both erosion and, significantly in the Flathead River basin, sedimentation in glacial Lake Missoula affected the altitude of the land surface (Levish, 1997). Unknowns in the timing of sedimentation and in the position of the ice–water contact at the terminus of Flathead lobe may contribute as much as 10–20% error to water-volume estimates. Use of these data, techniques, and assumptions resulted in a maximum estimated volume (at the 1265-m lake stand) of 2600 km^3, somewhat larger than Pardee's (1942) estimate of 2130 km^3. At a 1000-m lake stand the estimated volume is 450 km^3. At all lake stands, most of the lake volume was in the northern portion of the basin, along the Flathead River drainage (Fig. 2). Water that drained through the study area during lake lowering was only about 20% of the entire lake volume at the 1265-m stand; it was about 5% of the volume at a 1000-m stand.

Methods

Geologic mapping of unconsolidated deposits was done from 2002 to 2005 along the Clark Fork River valley and its tributaries from Missoula to Plains, Montana, and along parts of the Flathead River from Paradise to Dixon, Montana (Lonn and Smith, 2005 and unpublished mapping). Altitudes of deposits are obtained from 1:24,000-scale topographic maps and from 30-m scale DEMs. Deposits were described and measured mostly in exposures such as gravel pits and road-cuts; few natural exposures exist. The top of the bedrock surface and thickness of Quaternary deposits were also mapped using subsurface data consisting of 1750 descriptive lithologic logs made by drillers of water wells. After removing shallow and insufficiently detailed logs, the total thickness of silty glaciolacustrine and gravelly alluvial deposits could be mapped from about 150 well logs[1] in the 100-km-long canyon.

Stratigraphy and sedimentology of deposits

Unconsolidated Quaternary deposits in the Missoula valley and the canyon region along the Clark Fork River include

[1] The well-log data are available online at Montana Bureau of Mines and Geology's Ground-Water Information Center database (http://mbmggwic.mtech.edu).

gravelly alluvium and glaciolacustrine silt and clay. Gravelly alluvium occurs beneath terrace surfaces, in rolling uplands, and beneath most exposures of glaciolacustrine silt and clay. The silt and clay unit occurs mostly on incised uplands between 15 and 100 m above modern river level. These bench-forming sequences of laminated silt, clay, and minor sand have been widely recognized as deposits of glacial Lake Missoula (Pardee, 1910, 1942) and were informally called the Lake Missoula beds by Langton (1935). That terminology will be followed here. A few sections of the Lake Missoula beds have been described in various amounts of detail by Chambers (1971, 1984), Waitt (1980), Fritz and Smith (1993), and Levish (1997). The gravelly alluvium stratigraphically beneath the Lake Missoula beds has not been described in previous work. Interpretation of the gravelly alluvium is the focus of this study.

Gravelly alluvium

Gravelly deposits in the Clark Fork River canyon are composed mostly of grain-supported granule-, pebble-, and cobble-sized gravel. Interstices in the gravel are commonly open; however, coarse-grained sand occurs as a matrix within some gravel beds (Figs. 3 and 4). Silt and clay occupy interstices in some gravel units, especially within 1–2 m of overlying Lake Missoula beds. Clasts with intermediate diameters greater than 2–4 m (very coarse boulder- to block-sized clasts of Blair and McPherson, 1999) have been measured in outcrops. Discontinuous calcium carbonate coatings on clasts are locally common. Clasts are mostly composed of quartzite derived from the various Belt Supergroup formations, with lesser amounts of dolomitic rocks, diorite, and rare granitic rocks. Cobble- to boulder-sized clasts composed of weakly

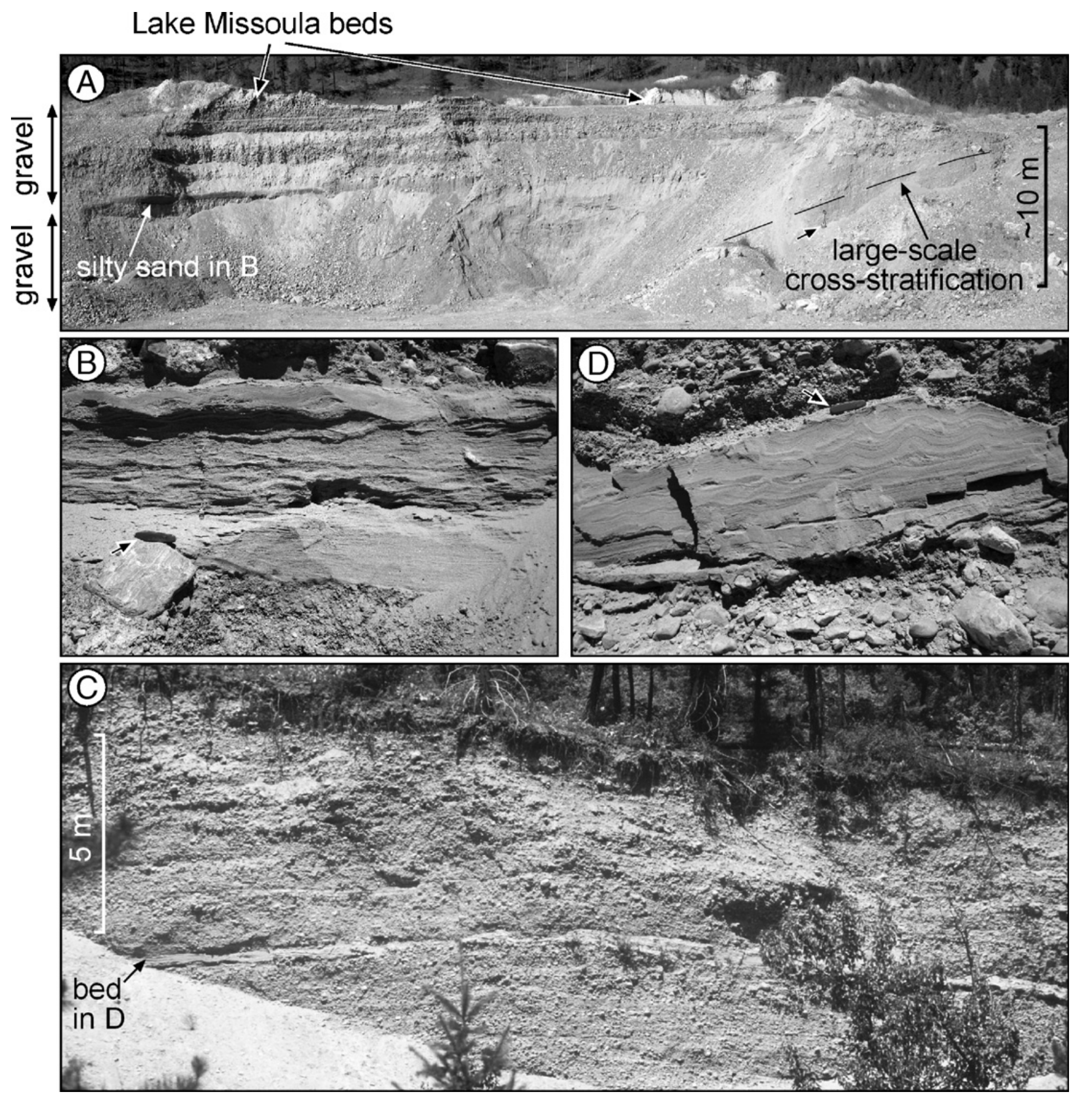

Figure 4. Gravelly alluvium and beds of fine-grained sand, silt, and clay. (A) Photo of two beds of gravelly alluvium separated by a silty sand bed. Lower gravel contains cross-stratification oriented down the Clark Fork River; upper gravel is capped by Lake Missoula beds; 1.25-m shovel at arrow. Latitude 47.2129°N, longitude 114.9355°W. (B) Detail of fining-upward sequence of very fine sand, silt, and clay separating gravel beds; scale is a 9-cm-long knife at arrow. (C) Gravelly alluvium and silty very fine-grained sand along Quartz Creek, 1.3 km upstream of its confluence with the Clark Fork River. Latitude 47.0251°N, longitude 114.7690°W. (D) Laminated sandy silt and very fine-grained sand; climbing ripples are oriented down valley (to right) and disrupted along ripple crests by fluid escape structures.

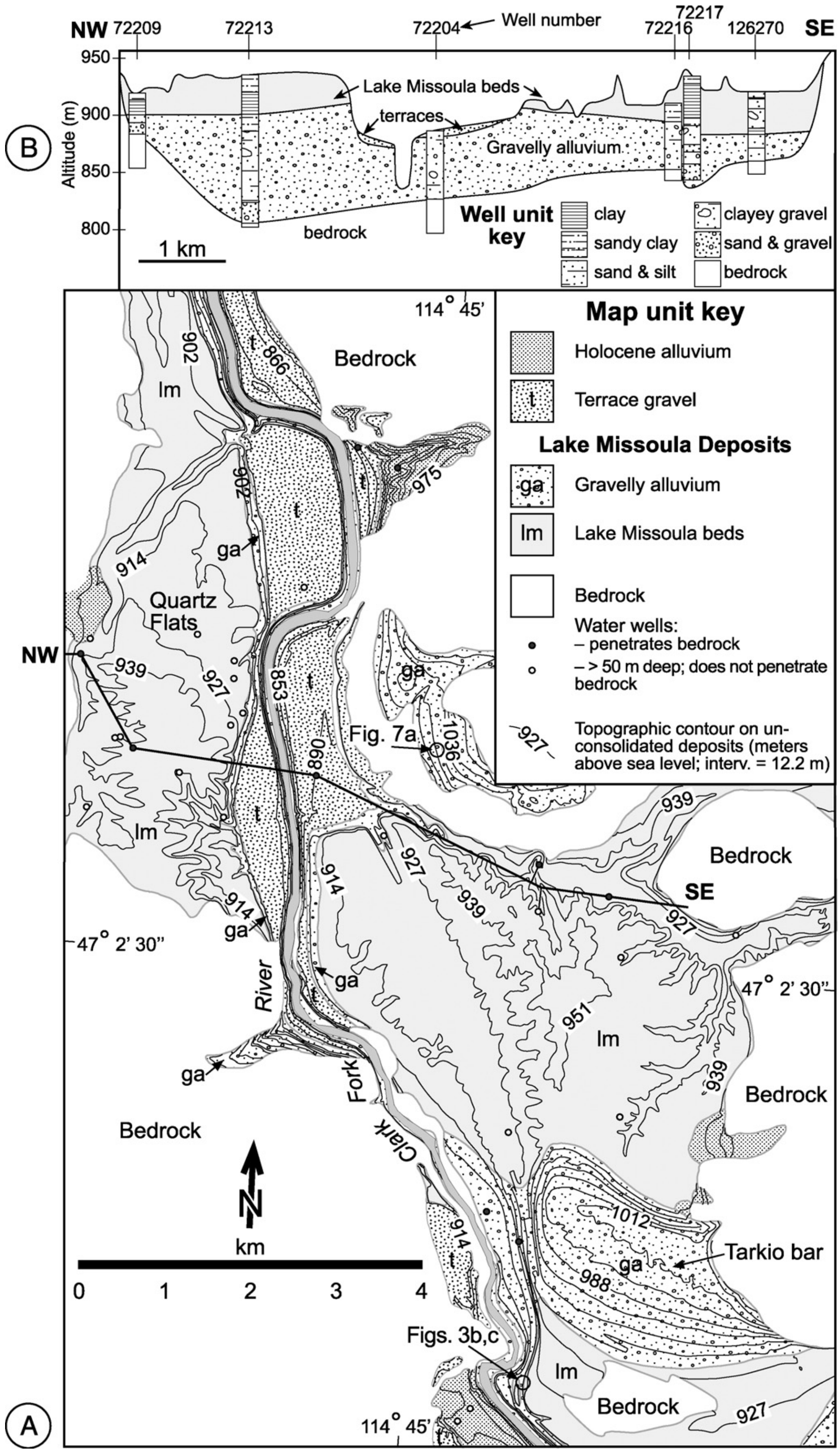

Figure 5. (A) Geologic map of deposits in the central portion of the study area. (B) Geologic cross section of unconsolidated deposits from lithologic logs of water wells; well data are in online database (http://mbmggwic.mtech.edu).

indurated mudstone and siltstone are common in a few exposures near the community of Tarkio (Fig. 2). These softer clasts are lithologically similar to Tertiary sedimentary rocks deposited in the Missoula and Ninemile valleys about 30–40 km upstream along the Clark Fork River.

The bedding in the gravelly alluvium includes cross-stratification with slipface heights of a few meters to >10 m and boulder-sized clasts that are locally imbricated (Figs. 3 and 4). Cross-stratification is made up of beds a few centimeters to 1–2 m thick of openwork pebbles and cobbles interbedded with poorly to very poorly sorted coarse-grained sand or granules. This cross-stratified sandy gravel is exposed in a few giant gravel bars along the Clark Fork River and in deposits near the confluence of tributary stream valleys with the Clark Fork River (Fig. 5). Stratification is not evident in all exposures; some exposures are of apparently massive, very poorly sorted gravel. Thick beds of gravel are locally interbedded with conspicuous thinner beds of cross-stratified very fine- and fine-grained sand, and laminated silt and clay (Fig. 4). The observed fine-grained beds are typically 20–150 cm thick, not bioturbated, and coarsen upward from laminated silt and clay to very fine- and fine-grained, climbing ripple cross-stratified sand (Figs. 4B and C). Fluid escape structures are locally common near the tops of the beds (Fig. 4B).

Regional mapping and topographic profiling show that much of the gravelly alluvium was deposited as gravel bars, especially downstream of narrow gorges in the Clark Fork River canyon (Fig. 6). Exposures in a few large-scale bedforms show that large-scale cross-stratified sets are capped by sets of smaller scale cross-stratification (Fig. 7A). Large-scale cross-stratification, block-sized gravel clasts, and large-scale gravel bars (Fig. 5) indicate that much of the gravelly alluvium along the Clark Fork River was deposited by high-velocity, high-discharge flows of water. The thin interbeds of laminated silt and clay and climbing ripple cross-stratified fine sand in the gravel deposits are interpreted to have been deposited in low-velocity phases of flood events or between different floods. The lack of bioturbation of the silty deposits suggests that the beds were not deposited in shallow, normal alluvial overbank environments. The presence of interbedded fine-

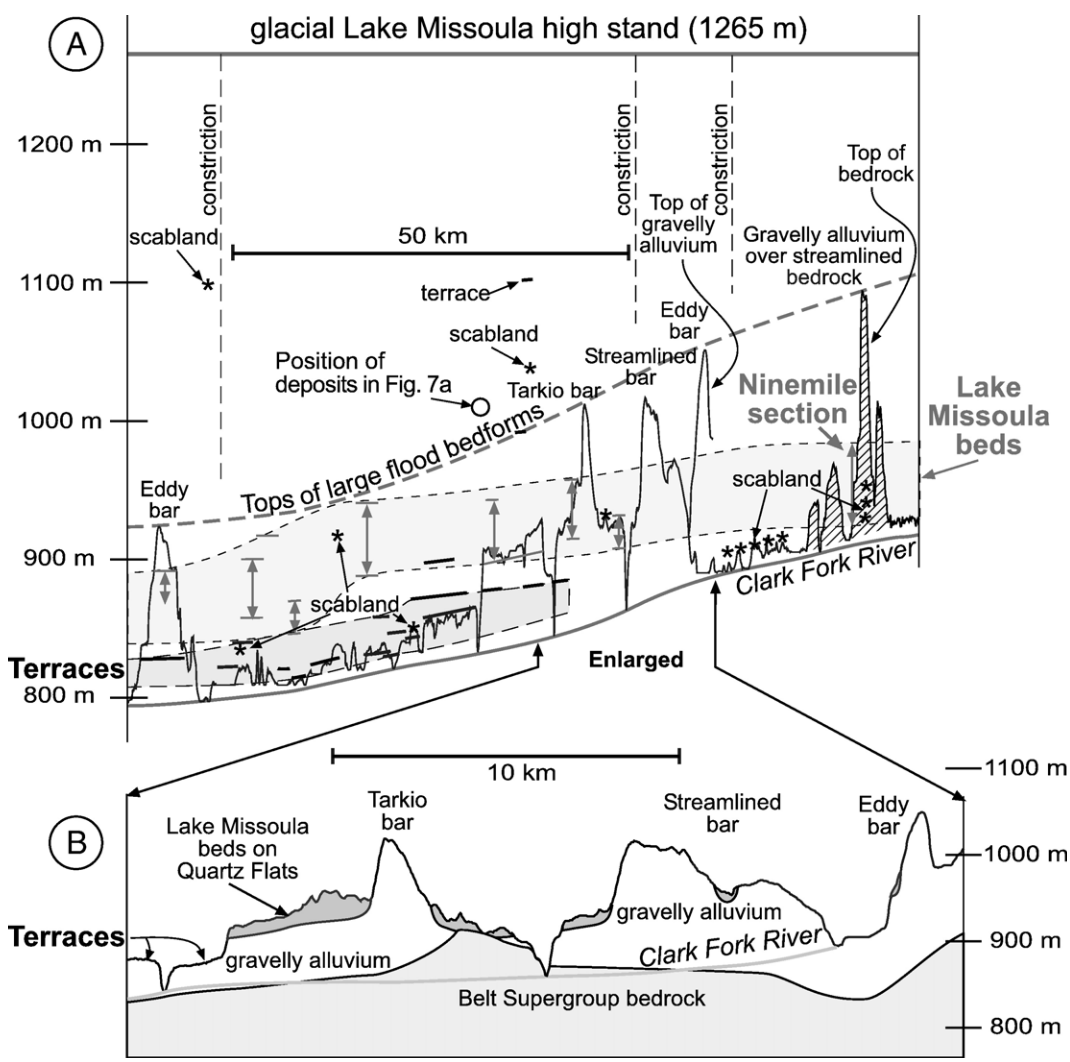

Figure 6. Topographic profile along the Clark Fork River valley, end points in Figure 2. (A) Two giant gravel bars and a streamlined, mid-channel bar show down-valley accretion; an eddy bar formed downstream of a bedrock constriction in the valley. (B) Glaciolacustrine silts overlie gravelly alluvium. The altitudinal distribution of scablands and terraces is indicated by dashes. The highest and lowest occurrences of glaciolacustrine silt and clay beds, such as the Ninemile section, are indicated by vertical arrows and dashes. All altitudes were horizontally projected onto the plane of the profile.

grained units in gravel sequences suggests that the gravelly alluvium may represent either multiple drainages of glacial Lake Missoula or temporary ponding, possibly due to flow constrictions in the canyon system during discharge events.

Glaciolacustrine silt and clay

Silt, clay, lesser amounts of sand, and rare gravel make up sequences 2–25 m thick of Lake Missoula beds that cap the gravelly alluvium unit. Silt and clay beds are characteristically laminated. Graded beds, cross-stratification, and climbing ripples occur in typically continuous, very fine- to fine-grained sandy beds. Rare coarse-grained sand, granules, and pebbles within the predominantly silty and clayey unit are typically in lenticular beds that show basal scours with less than 1 m of relief. Exposed beds of the coarser grained sediment are two to 50 cm thick, and crop out over distances of a meter to about 10 m (Chambers, 1971, 1984).

Where the Lake Missoula beds overlie gravelly alluvium, the contact is typically abrupt. Two locations were found where basal silt and clay beds show soft-sediment deformation where they overlie gravelly alluvium. At one location about 3 m of total displacement occurred along a series of faults that die out upwards into the lower part of the Lake Missoula beds (Figs. 3B and C).

The silt and clay sequences are lacustrine deposits of glacial Lake Missoula. Silt and clay interbeds in the sequences have been interpreted as varves (Alt and Chambers, 1970; Chambers, 1971, 1984; Waitt, 1980, 1985; Fritz and Smith, 1993; Levish, 1997). Cross-stratified sandy beds have been interpreted as due to currents generated by complete lake drainage (Alt and Chambers, 1970; Curry, 1977; Waitt, 1980, 1985; Atwater et al., 2000), due to currents or lake-level fluctuations in a shallow lake (Chambers, 1971, 1984; Fritz and Smith, 1993), or due to deep-lake currents (Shaw et al., 1999). Whatever the specific environment of deposition, the continuous, unbioturbated nature of each laminated silt and clay sequence indicates deposition in one or more stands of glacial Lake Missoula.

The laterally discontinuous bedding and rare occurrence of coarse-grained sand and gravelly facies in the deposits suggest local, episodic deposition. The deposits likely represent localized, high-energy subaqueous flows on the lake bottom. They may be the result of alluvial or debris-flow inputs to the lake from stream valleys or escarpments in the canyon, or in areas of the lake basin close to valley glaciers (Fig. 2), they may be proglacial deposits.

Soft-sediment disruption of bedding observed near the bottom of some sequences shows that slumping of underlying gravel evidently took place locally during refilling of the glacial lake. As the gravelly alluvium deposited during a previous lake drainage event was resaturated with water during lake transgression, the sediments apparently failed toward topographic lows left by the previous drainage event (Figs. 3B and C).

Post-flood and Holocene deposits

Holocene deposits make up little of the fill in the valley. Unconsolidated alluvium occurs along modern stream floodplains, on terraces, and on some alluvial fans at canyon mouths

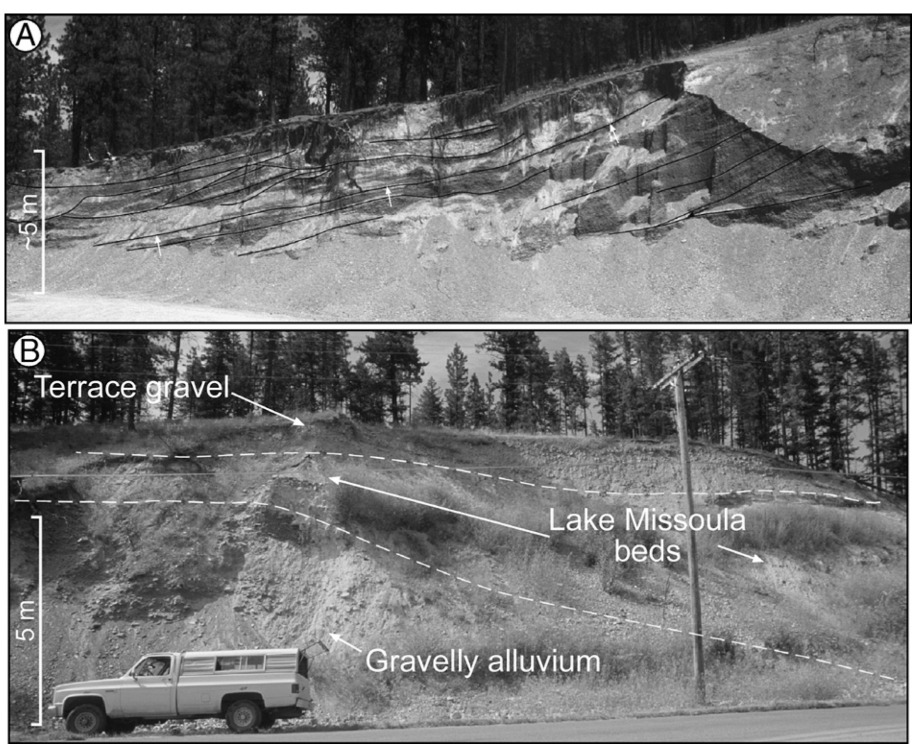

Figure 7. (A) Photograph of about 5 m of gravelly alluvium shows sets of large-scale cross-stratification low in the exposed section overlain by sets of cross-cutting trough cross-stratification. The highest recognized large-scale cross-strata are indicated by white arrows. The stratification sequence is interpreted to represent a bedform built during high-stage flows (large-scale cross-strata) that was reworked during falling-stage flows (trough cross-strata); location in Figure 5. (B) View north of gravelly alluvium and glaciolacustrine silt and clay capped by 2–3 m of gravel underlying a terrace about 30 m above the Clark Fork River near its confluence with Cedar Creek (Fig. 2). Latitude 47.1757°N, longitude 114.8746°W.

Table 1
Characteristic features of high-energy megafloods

Feature	Selected previous examples	This study area
Streamlined forms	Baker (1978), Komar (1983, 1984)	Streamlined gravel bar and bedrock (Fig. 6)
Giant flood dunes and bars, in main channels and eddy bars in tributaries	Bretz et al. (1956), Baker (1973), Carling et al. (2002)	Giant gravel bars; 100–150 m high
Transport of coarse sediment in suspension	Komar (1980), O'Connor (1993)	Pebbles, cobbles, and boulders deposited on giant gravel bars
Weakly indurated clasts in deposits	Bretz (1928), Baker (1978)	Tertiary sedimentary rock clasts in Tarkio gravel bar
Sorted, open-framework gravels	Bretz (1923), Baker (1978), Carling et al. (2002)	Pebble, cobble, and boulder openwork gravel in gravelly alluvium foresets (Fig. 6)
Imbricated very coarse-grained boulders	Bretz et al. (1956), Baker (1973), O'Connor (1993)	Coarse- to very coarse-grained imbricated boulders.

(Fig. 5). Colluvium is common on and near the bases of slopes. Where these deposits are associated with characteristic topographic features (such as bar and swale topography and conical landforms) or they overlie paleosols, they are easily separated from deposits associated with the drainage of glacial Lake Missoula. The occurrence of glaciolacustrine silt and clay deposits in sequences of sand and gravel below terrace surfaces is useful for separating the upper, possible Holocene sand and gravel from older Pleistocene sand and gravel. Most of the gravel pits in the canyon contain either gravel with very large scale (2–10 m) cross-stratification or glaciolacustrine silt and clay sequences, suggesting that they are glacial Lake Missoula deposits. Sand and gravel immediately beneath terrace surfaces and above glacial Lake Missoula deposits are typically less than 3 m thick (Fig. 7B).

Physiography

The landforms composed of gravelly alluvium in the canyon reach of the Clark Fork River shows a series of gravel bars. The Tarkio gravel bar developed downstream from a canyon, where the valley opened and flow forces decreased near Quartz Flats (Fig. 5). Two eddy bars, those with steep lee faces oriented up

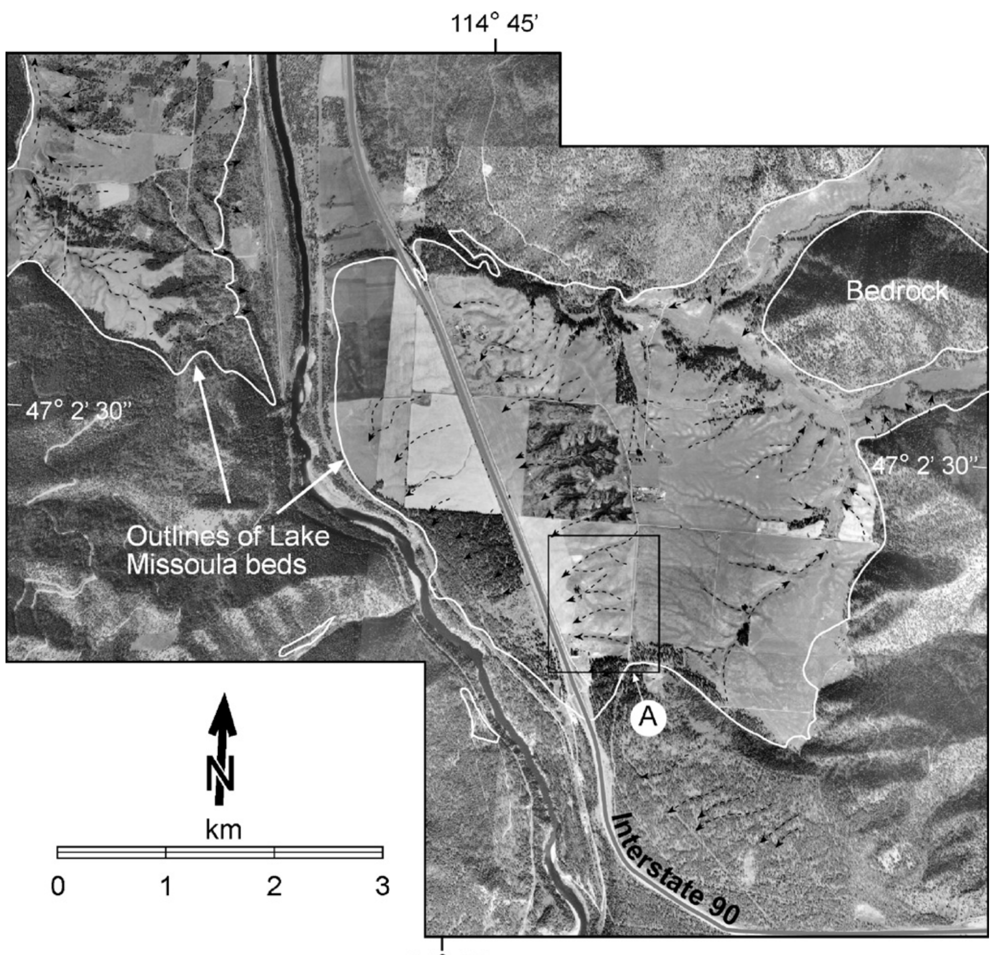

Figure 8. Digital orthophoto quadrangles of part of the area shown in Figure 5. Streams are inactive or intermittent in the valley systems shown by dashed arrows. (A) = rolling topography previously interpreted as a down-valley train of giant dunes.

tributary valleys, show deposition by current eddies (Fig. 6). Similar deposits and landforms have been recognized in the Channeled Scabland flood route, outside the glacial lake basin (Table 1). The similar heights above local base level of this gravelly alluvium suggest it can be correlated with the eddy bars along the Flathead and lower Clark Fork rivers and with the flood dunes on the Camas Prairie (Pardee, 1942), termed the “flood gravel subfacies” by Chambers (1984).

Scabland topography in the glacial Lake Missoula drainage basin is an erosional landform where bedrock is stripped of most overlying unconsolidated sediments along a surface characterized by internally drained basins. As in the Channeled Scablands of Washington, scablands along the Clark Fork River are evidence for high-velocity flows associated with the drainage of glacial Lake Missoula. Scablands along canyon walls above the levels of Lake Missoula beds are evidence for deep flood events. Scablands near the Clark Fork River below the glaciolacustrine deposits likely resulted from drainage(s) of the lake(s) that deposited the Lake Missoula beds (Fig. 6). Scabland topography was mapped within 9 m of the Clark Fork River level in the study area (Fig. 6), and less than 5 m above river level in the Flathead River canyon. Block-sized boulders (with intermediate diameters of 4–10 m), recent colluvium, and soil are the only deposits in these irregular landforms. There is no evidence that these features are exhumed. The presence of this topography and imbricated boulder gravel near modern base level shows that, at least in some areas, the rivers cut down to near the present levels in floods related to the last draining(s) of glacial Lake Missoula.

Networks of dry paleovalleys are incised mostly into the Lake Missoula beds; a few are in gravelly alluvium (Fig. 8). Mapping of these valleys was based on field observations, the topographic contours in Figure 5, and the photographs in Figure 8. These networks are expressed as generally flat-bottomed valleys that have no active through-going drainage. Some valleys that drain higher terrains have active drainages that are dramatically underfit for the valley widths. Some valleys display meandering planforms, although no active drainages in the valleys or drainages are intermittent streams with bank widths less than one-tenth the flat-bottomed valley width. The mouths of inactive valleys are near the levels of terraces along the Clark Fork River. Minimal sediment accumulations exist at the lower ends of the valleys, as shown by the lack of fan-shaped accumulations just west of the Clark Fork River in the center of Figure 5.

From ground level, the valley networks produce an apparent rolling topography on the Lake Missoula beds. This rolling topography has been interpreted as down-valley-oriented 5- to 10-m-high dunes formed by high-velocity lake drainage events (Alt, 2001, p. 76–77). Geologic mapping, however, shows these landforms are cut into glaciolacustrine silts as part of a relict parallel-to-dendritic erosional valley system. Although some valleys are occupied by Holocene stream systems emanating from side bedrock valleys and some are sites of active gullying and extension, most of the valley systems are inactive. The topography is interpreted here to be a set of drainage networks established as the water drained across the landscape as the last stand of glacial Lake Missoula receded. The networks were mostly abandoned once the glaciolacustrine deposits dewatered.

A series of alluvial terraces with 0 to 5 m of gravel fill exists along the Clark Fork River in the study reach, typically where the valley is less constricted by bedrock and the valley is underlain by gravelly alluvium (Fig. 6A). Most terrace heights above the Clark Fork River range from seven to 50 m. Dry valley networks in the topographically higher Lake Missoula bed-covered benches do not extend across the terrace surfaces. Some drainage networks directly discharge onto terrace surfaces (Fig. 8). These relationships show that the terraces formed during or after the last lake draining as the Clark Fork River downcut through older flood deposits, lake deposits, and bedrock.

Discussion

Discovery of large-scale bedforms made up of gravelly alluvial deposits along the Clark Fork River contributes to our understanding of the depositional record within the glacial Lake Missoula basin. Gravelly alluvium that makes up the gravel bars and that is stratigraphically beneath Lake Missoula beds, like the Ninemile section, must represent vigorous discharge events that pre-date the silt sections. Like the deposition of eddy bars at levels 20–300 m above the Flathead and lower Clark Fork rivers, the large-scale bedforms up to 170 m above local base level attest to one or more catastrophic drainings of glacial Lake Missoula. For example, the altitude of the top of the gravel bar near Tarkio (Fig. 5) is within 20 m of the top of the “Stout’s Bar” eddy bar at Perma (Pardee, 1942). Evidence from the bars themselves for multiple depositional events has not been found to date. It is possible that reactivation surfaces in these deposits could be found to show deposition during more than one event.

A profile of the tops of the bedforms may approximately parallel the water-surface profile during construction of the bedforms (Fig. 6). Although the profile may approximate a water-surface slope, the lack of evidence for water-surface heights, such as deposits resulting from flood waters spilling over local divides (Benito and O’Connor, 2003), makes reconstruction of flood-surface heights and flow modeling difficult.

Because the Lake Missoula beds overlie the gravelly alluvium, the lake stand(s) that deposited the finer grained sequences, like the Ninemile section, were more recent. The depositional record and preserved landforms show that flood magnitudes must have decreased over time, a conclusion similar to that of Pardee (1942), Chambers (1984), O’Connor and Baker (1992), and Benito and O’Connor (2003). However, contrary to earlier interpretations of the Ninemile section (Waitt, 1980, 1985; Atwater et al., 2000), most evidence for catastrophic floods from glacial Lake Missoula predates the Ninemile section of deposits. Although it is possible that the section records multiple lake drainings (Chambers, 1971; Waitt, 1980, 1985; Atwater et al., 2000), it may be interpreted to record fluctuating stands in a lake that did not necessarily drain catastrophically (Chambers, 1984; Fritz and Smith, 1993).

Paleoincision surfaces in the Lake Missoula beds have not been recognized or described in the literature. If the Lake Missoula beds were deposited during numerous lake filling and draining cycles (Waitt, 1980, 1985; Atwater et al., 2000), incision networks, like those on the upper surface, are expected to be found in the stratigraphic sections. Because of this, bed-to-bed correlation of rhythmites in the Ninemile section with sequences attributable to catastrophic floods outside the basin (Waitt, 1980, 1985; Atwater et al., 2000) is problematic. The sedimentary record of the Lake Missoula beds is interpreted here to reflect one or possibly more late, probably shallow, stands of glacial Lake Missoula. Further analysis of Lake Missoula beds, including the Ninemile section, is needed for understanding of the late lake-level history.

The position of scabland within 10 m of the Clark Fork River, preservation of Lake Missoula beds on upper benches, and the preservation of relict stream networks cut into the Lake Missoula beds suggests that the last lake was shallow. If the water height above the silt unit was shallow, the bottom currents capable of significant bed erosion would have formed after water dropped to a level where the silt-covered benches were exposed. Alternatively, if the last lake was relatively deep, the last drainage event must have occurred at a slower rate than the previous events, causing lower velocity flooding. This alternative hypothesis would require a slower, less catastrophic failure of the ice dam than during the earlier flood(s). In either case, significant erosion during the lake's last draining was concentrated along the inner canyon of the Clark Fork River. Some terrace surfaces inset into the glaciolacustrine sediments were produced during this last lake drainage, similar to the example described by Carling et al. (2002). The existence of scabland topography in bedrock below some terraces shows that those terrace surfaces were abandoned during the last drainage of glacial Lake Missoula. Sediment eroded from the valley networks was carried downstream along the inner canyon as flood waters swept across these terraces. Field relations suggest that terraces more than 5–10 m above the Clark Fork River may have been formed by erosion and minor deposition during draining of the last glacial Lake Missoula.

Comparing this shallower stand of glacial Lake Missoula with other features in the basin suggests possible correlations of deposits. Shoreline features and glacial moraines in the Flathead valley portion of the lake basin at altitudes between 1050 and 1150 m suggest that the glacial lake stood near these levels when valley glaciers built moraines (Levish, 1997, p. 120–121). In his analysis of glacial Lake Missoula deposits between altitudes of 770 and 970 m, Levish did not find any incisions supporting more than one draining event. These observations are compatible with the conclusion that much of the Lake Missoula beds, including the Ninemile section and the lake deposits in the Flathead River area, were deposited in a shallower, late glacial Lake Missoula. The maximum stand for this lake was possibly between 1050 and 1150 m. This is similar to the 1080-m altitude for a lake suggested by O'Connor and Baker (1992, p. 277) in which the silts noted by Pardee (1942) were deposited.

The preservation of greater amounts of gravelly alluvial deposits along the Clark Fork River upstream of the Flathead River than along either the lower Clark Fork or the Flathead may be due to the dimensions and geometry of the lake basin. The Flathead River basin and the lower Clark Fork River basin, downstream of its confluence with the Flathead, contained the vast majority of the water at all possible lake levels (Fig. 2). Water in the lake above the study reach was only about 15% of the entire lake at maximum lake level. Because most of the water flowed through the Flathead River canyon, and all of it flowed through the lower Clark Fork River canyon, the preservation potential of early flood deposits was low. Flood deposits in these lower reaches are restricted to backwater areas, the eddy bars.

Conclusions

Gravelly alluvial deposits stratigraphically beneath the long-recognized glacial Lake Missoula deposits at the Ninemile section indicate that catastrophic flood(s) preceded deposition of these deposits. Interbeds of laminated silt and fine-grained sand in the gravelly alluvium suggest that multiple large floods may have created the deposits; however, slackwater deposition during hydraulic ponding or waning stages of individual floods cannot be ruled out. The preservation of erodible, Lake Missoula beds across flood gravel alluvium shows that the largest flows in the canyon were the earliest. The sedimentology and lack of deeply incised paleochannels recognized in the Lake Missoula beds suggests that the unit was deposited in a lake that underwent fluctuating depths. However, multiple drainages cannot be ruled out. These beds were incised during final lake lowering, probably by drainage of a lake where high-velocity flows were constrained to the area along the inner valley of the Clark Fork River.

Specific conclusions of this study are:

(1) The large-scale erosional and depositional landforms (most scablands, eddy bars, and streamlined landforms) were produced by one or more floods from earlier, deeper lake(s) (>1200-m stand(s)).
(2) The Lake Missoula beds, including the Ninemile section, and possibly the thick glacial Lake Missoula deposits along the Flathead River, were deposited in one or more later, shallower lakes (~1050–1150 m stand(s)).
(3) The last lake drainage(s) were less catastrophic than earlier ones, leaving a rolling topography of relict channels on upland glacial-lake silt and clay deposits and strath terraces and scablands to within a few meters of current base level.

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