Quaternary Science Reviews 133 (2016) 62–76

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Record of glacial Lake Missoula floods in glacial Lake Columbia, Washington

Michelle A. Hanson [a, *], John J. Clague [b]

[a] Saskatchewan Geological Survey, 1000–2103 11th Avenue, Regina, Saskatchewan S4P 3Z8, Canada
[b] Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada

ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
12 December 2015
Accepted 14 December 2015
Available online 29 December 2015

Keywords:
Glacial Lake Missoula
Glacial Lake Columbia
Outburst floods
Stratigraphy
Sedimentology

ABSTRACT

During the last glaciation (marine oxygen isotope stage 2), outburst floods from glacial Lake Missoula deposited diagnostic sediments within glacial Lake Columbia. Two dominant outburst flood lithofacies are present within glacial Lake Columbia deposits: a flood expansion bar facies and a finer-grained hyperpycnite facies. We conclude that the flood sediments have a glacial Lake Missoula source because: (1) current indicators indicate westward flow through the lake, and upvalley flow followed by downvalley flow in tributary valleys; (2) no flood sediments are found north of a certain point; (3) there is a dominance of Belt–Purcell Supergroup clasts in a flood expansion bar; and (4) some of the finer-grained beds have a pink colour, reflective of glacial Lake Missoula lake-bottom sediments. A new radiocarbon age of 13,400 ± 100 $^{14}$C BP on plant detritus found below 37 flood beds helps constrain the timing of outburst flooding from glacial Lake Missoula.



## 1. Introduction

During the Fraser Glaciation (marine oxygen isotope stage 2), outburst flooding from glacial Lake Missoula significantly modified the landscape of eastern Washington (Bretz, 1928, 1923; Waitt, 1980). Within this landscape was glacial Lake Columbia, which existed due to damming of the Columbia River by the Okanogan lobe of the Cordilleran ice sheet (Fig. 1A; Atwater, 1986, 1984; Bretz, 1932; Flint, 1935; Waitt and Thorson, 1983). Farther east, the Purcell Trench lobe dammed the Clark Fork River in northern Idaho, impounding glacial Lake Missoula in Montana (Fig. 1A; Pardee, 1942, 1910). Glacial Lake Missoula had no subaerial outlet, but it drained when water reached a threshold depth against the damming ice. Failure of the dam and emptying of the lake producied outburst floods with peak discharges of up to 17 million $m^3s^{-1}$ that lasted days to weeks (Baker, 1973; Clarke et al., 1984; Craig, 1987; Denlinger and O'Connell, 2010; O'Connor and Baker, 1992). After the lake emptied, the ice dam reformed and the process repeated itself. As many as 89 floods occurred over a period of approximately 2000 years during the Fraser Glaciation (Atwater, 1986; Clague et al., 2003).

Glacial Lake Columbia was in the direct path of these outburst floods. Floodwaters flowed through glacial Lake Columbia along different routes and with different outlets, depending on the depth of the lake and the configuration of the Okanogan and the Columbia River ice lobes. For most of the lake's existence, the Okanogan lobe dammed Columbia River downstream of Grand Coulee (Fig. 1A), forming a low-level lake at ~500 m above sea level (asl; Fig. 1B; Atwater, 1987, 1986). At this low level, floodwaters drained from glacial Lake Columbia via Grand Coulee (465 m asl; Atwater, 1987, 1986). At its maximum, however, the Okanagan lobe terminated at the Withrow moraine, blocking Grand Coulee (Fig. 1A; Atwater, 1987, 1986; Flint, 1937, 1935; Flint and Irwin, 1939; Kovanen and Slaymaker, 2004), and glacial Lake Missoula floodwaters drained at higher elevations along the southern margin of the lake, at the Cheney divide (702 m asl) and the Hawk Creek divide (710 m asl; Fig. 1A; Atwater, 1987, 1986). This high-level lake, which may have lasted for about two centuries, attenuated the effects of glacial Lake Missoula floodwaters (Atwater, 1986). The presence of ice-rafted erratics at elevations up to ~750 m asl indicates that the lake swelled during flooding from glacial Lake Missoula (Atwater, 1986). For a short period, a maximally extended Columbia River lobe blocked the confluence area of the Columbia and Spokane rivers and temporarily divided the lake in two (Atwater, 1986; Flint, 1937, 1936; Pardee, 1918; Richmond et al., 1965; Waitt and Thorson, 1983). Atwater (1986) argued that anomalously thin flood beds

* Corresponding author.
E-mail addresses: Michelle.Hanson@gov.sk.ca (M.A. Hanson), jclague@sfu.ca (J.J. Clague).

http://dx.doi.org/10.1016/j.quascirev.2015.12.009
0277-3791/

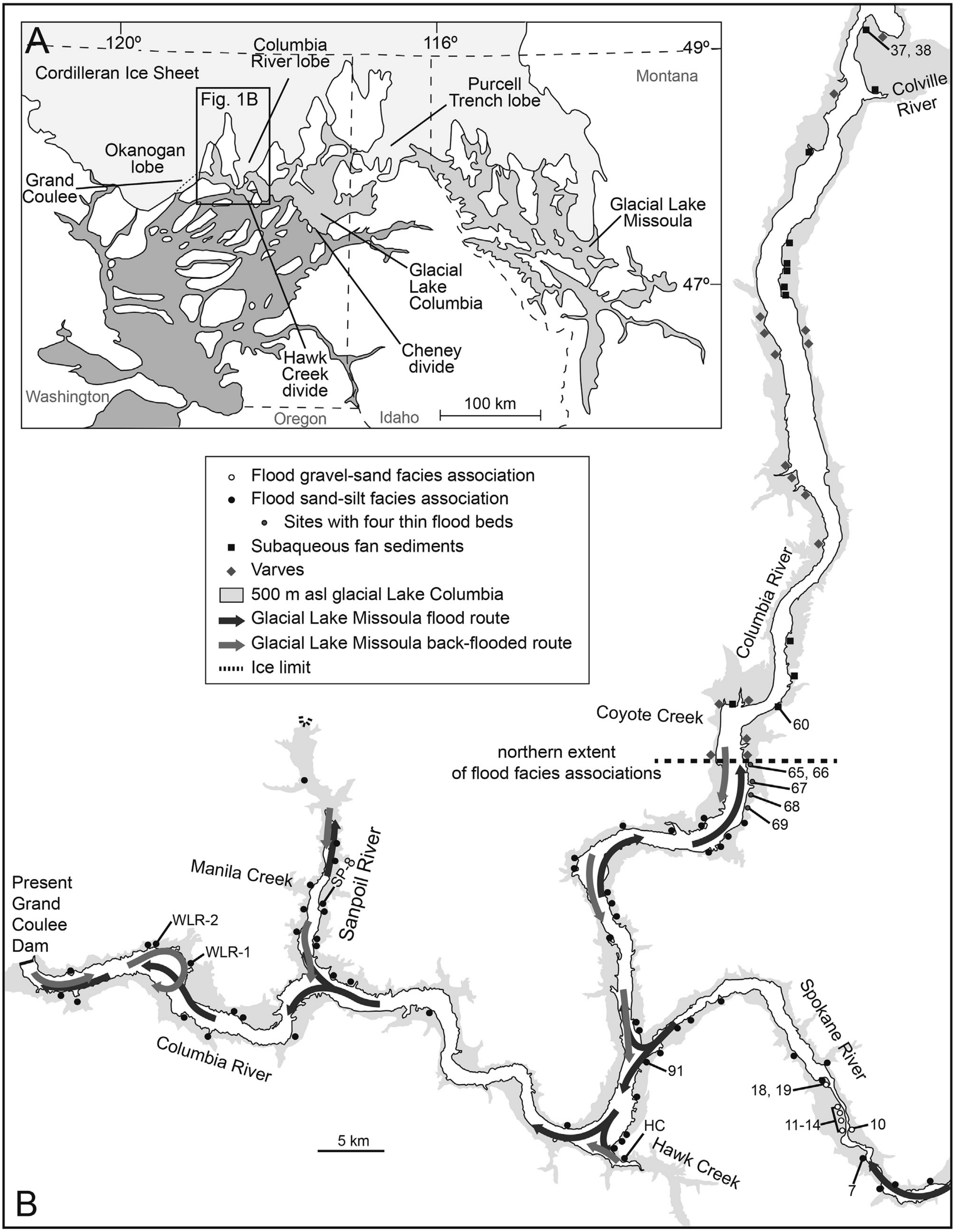


**Fig. 1.** (A) Study area showing locations mentioned in the text and the maximum extents of the Cordilleran ice sheet and of glacial Lake Columbia; darkest grey highlights glacial Lake Missoula floodpaths; dashed line under the Okanogan lobe shows the extent of the Grand Coulee (adapted from Atwater, 1986; Levish, 1997; Waitt, 1985). (B) Franklin D. Roosevelt Lake, Washington (white); the grey area is the areal extent of glacial Lake Columbia at the 500 m asl stage. Representative sites are shown. Symbols refer to the dominant lithofacies association at each site; other lithofacies associations may be present. (Sanpoil Valley area of figure adapted from Atwater, 1986.)

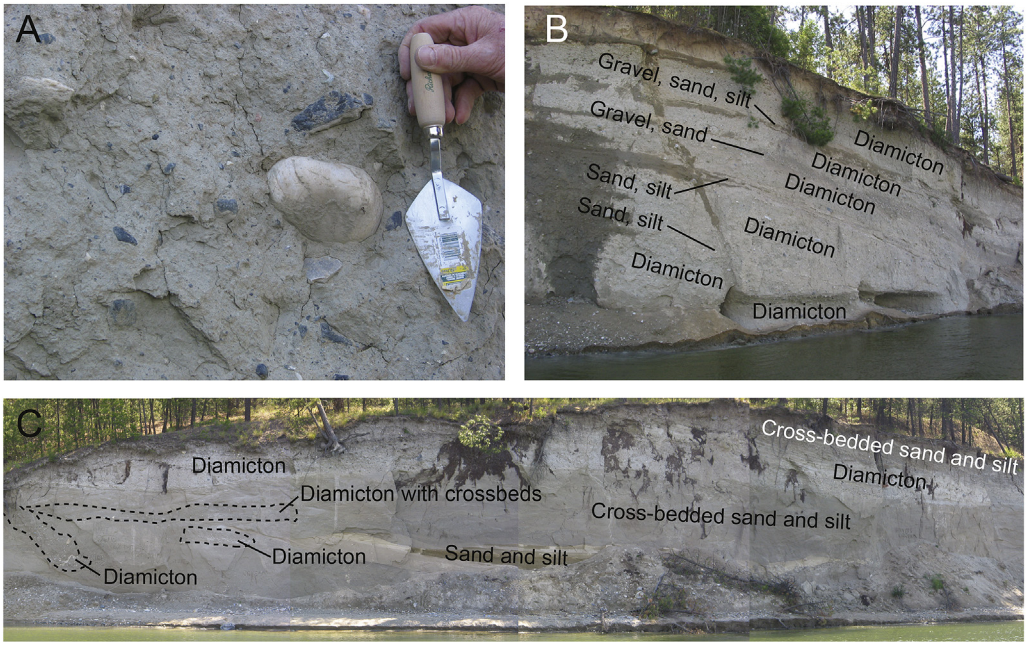


**Fig. 2.** Subaqueous fan deposits. (A) Diamicton (site 38). The diamicton is massive, poorly sorted, and moderately compact, with ~5% subangular to subrounded clasts. (B) A horizontal diamicton bed overlain by five diamicton beds dipping ~9° southward (site 38). The diamicton beds are separated by outwash beds of poorly sorted gravel, sand, and minor silt. (C) Massive, poorly sorted diamicton overlain and underlain by trough and planar cross-bedded gravelly sand and silt (site 37). The diamicton pinches out to the south (right). The lower sand and silt unit contains lenses of similar diamicton that truncate the sand and silt and contain rip-ups of silt. One of the diamicton lenses has downvalley-oriented cross-beds and clasts along its lower contact.

near Manila Creek were the product of attenuation of floodwaters by a fully extended Columbia River lobe and inferred that the lobe sat at this maximum position for approximately one to two centuries around 15,350 $^{14}$C yr BP.

Pardee (1918) was the first to recognise glaciolacustrine sediments in the glacial Lake Columbia area. He named them the "Nespelem silt" and described them as fine white silt with interbedded gravel. Other early researchers presented evidence for the advance of the Columbia River lobe southward (Flint, 1936; Jones et al., 1961) and described coarse sediments interbedded with glaciolacustrine sediments that would later be recognized as evidence for the flow of glacial Lake Missoula floodwaters into glacial Lake Columbia. Subsequent research of exposures of glacial Lake Columbia sediment focussed on beds attributed to outburst floods from glacial Lake Missoula (Richmond et al., 1965; Waitt, 1984; Waitt and Thorson, 1983). The most significant body of work done on glacial Lake Columbia sediments and interbedded glacial Lake Missoula sediments is that of Atwater (1987, 1986, 1984) in the Sanpoil River valley and Manila Creek area (Fig. 1B). He presented evidence for 89 glacial Lake Missoula flood-laid beds interbedded with fine-grained glaciolacustrine sediment.

This paper describes and discusses glaciolacustrine and glacial Lake Missoula flood-laid beds in the west part of former glacial Lake Columbia. It is based on examination of 128 exposures, including six exposures previously described by Atwater (1986) in the Sanpoil River valley. One new radiocarbon age further constrains the timing of glacial Lake Missoula flooding during the Late Pleistocene.

## 2. Study area

Sediments deposited in glacial Lake Columbia are extensively exposed along Franklin D. Roosevelt Lake in northeast Washington (Fig. 1B). The lake is impounded behind Grand Coulee Dam near where the Okanogan lobe dammed the Columbia River at the peak of the Fraser Glaciation. Lake Roosevelt is 107 m deep at the dam and extends upstream almost to the Canada–United States International Boundary. It has an area of approximately 325 km$^2$ and a perimeter of 965 km. The major streams flowing into the lake include the Sanpoil River, Hawk Creek, the Spokane River, and the Colville River (Fig. 1B). We surveyed the lake shoreline over a distance of 170 km from Grand Coulee Dam upstream to just north of the Colville River, 16 km up the Sanpoil River valley, and 45 km up the Spokane River valley (Fig. 1B).

## 3. Methods

We accessed most exposures along Lake Roosevelt by boat and a few sites by roads. We described exposures, noting unit thickness, the nature of contacts between units, grain size, sorting, clast support, and sedimentary structures, including flow direction indicators.

Lithofacies types presented below (Section 4) follow the terminology of Miall (1978, 1977) and Eyles et al. (1983), but without the lithofacies codes. The terminology applied to flood sediments (Section 5) is based on the jökulhlaup (glacier outburst flood) lithofacies types of Maizels (1997, 1993). We group lithofacies into associations where appropriate to interpret depositional environments. For descriptive purposes, we divide the outburst flood sediments deposited in glacial Lake Columbia into two groups based on the magnitude of the floods.

## 4. Description and interpretation of glacial Lake Columbia sediment

### 4.1. Diamicton-gravel-sand facies association

The diamicton-gravel-sand facies association is exposed at several places along the shoreline of Roosevelt Lake north of the mouth of the Spokane River ('subaqueous fan sediments', Fig. 1B). We examined several exposures of these sediments north of the

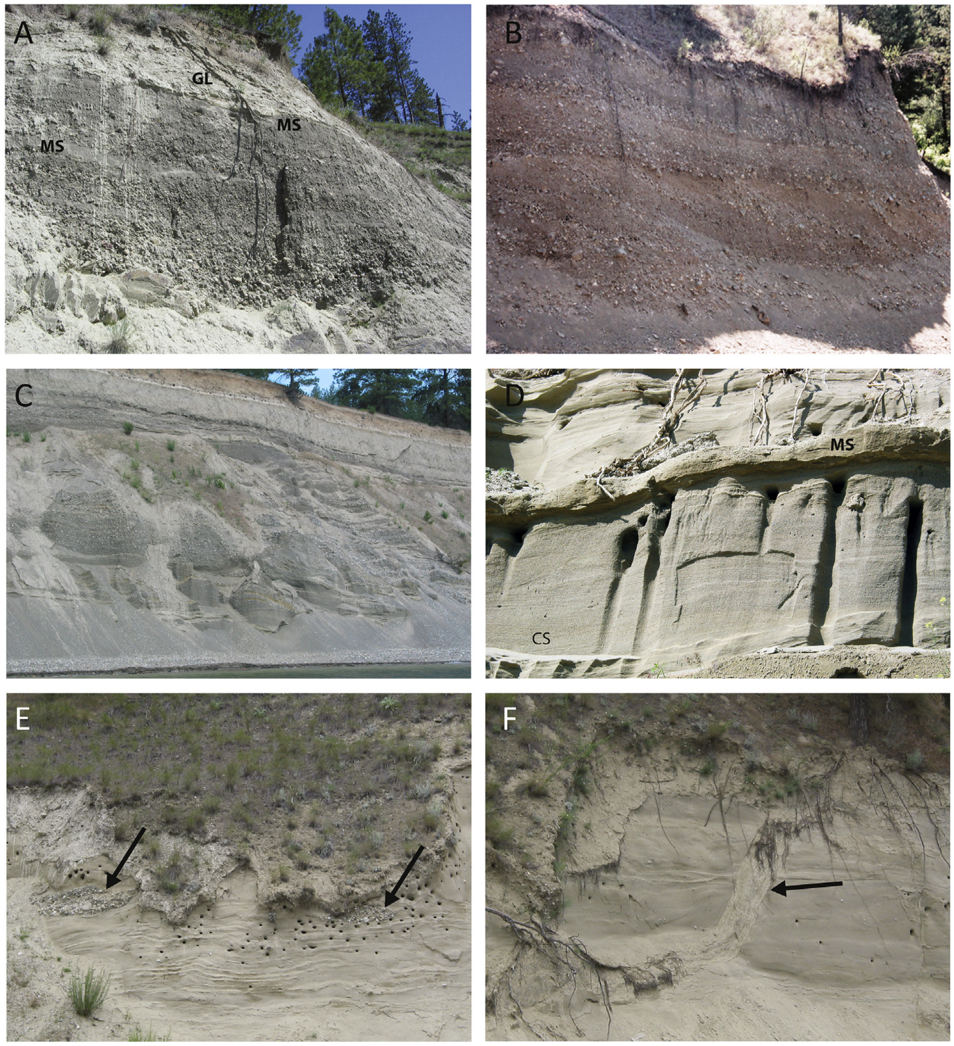


**Fig. 3.** Subaqueous outwash deposited in front of the Columbia River lobe. (A) Clast-supported, planar-inclined, imbricated cobble gravel. The gravel grades up into pebble-cobble gravel and contains interbeds of massive pebbly sand (MS). This sequence is overlain by glaciolacustrine sand and silt (GL). (B) Normally graded planar-inclined beds of pebble-cobble gravel and sand overlain by normally graded horizontal beds of pebble-cobble gravel and sand (site 60). (C) Interbedded pebble-cobble gravel, sand, and silt. (D) Trough cross-bedded coarse to medium sand (CS) and interbeds of massive fine sand (MS). (E) Bedded and massive sand and silt containing ice-rafted gravel (arrows). (F) Massive and bedded sand cross-cut by a vertically laminated dike (arrow).

Colville River (Fig. 1B). The diamicton contains lenses of silt and sand, and is moderately compact, massive, poorly sorted, has a sandy silt matrix, and contains 5–25% subangular to subrounded clasts ranging from granules to boulders up to 1.5 m in diameter (Fig. 2A). Some clasts are striated and faceted. We describe the facies at two well-exposed representative sites.

At site 38 (Figs. 1 and 2B), five diamicton beds ranging in thickness from 1 to 3.5 m dip approximately 9° southward. These beds are separated conformably by bedded to graded layers of poorly sorted gravel, sand, and minor silt ranging from a few centimetres to ~1 m thick.

At site 37 (Figs. 1B and 2C), a similar diamicton sharply overlies trough cross-bedded and inclined planar-bedded sand and silt with gravel lenses. The diamicton pinches out to the south (down-ice) and is conformably overlain by inclined and trough cross-bedded gravelly sand and silt. This upper stratified unit coarsens upward and contains a few lenses of gravel up to 20 cm long that deform underlying beds. The lower stratified unit contains lenses of diamicton with clasts of silt up to 20 cm long. The diamicton lenses truncate the sand and silt. Most of the diamicton lenses are massive, but one has faint downvalley cross-bedding and a concentration of clasts along its lower contact.

The diamicton-gravel-sand facies association was likely deposited on grounding-line subaqueous fans ('subaqueous fan sediments', Fig. 1B) in glacial Lake Columbia at the front of the Columbia River lobe as it retreated northward. There is no evidence that these deposits were overridden by an advancing glacier.

The diamicton beds at site 38 were deposited by non-erosive, non-channelised subaqueous debris flows (Benn, 1996; Eyles and Clague, 1991; Eyles and McCabe, 1989), flowing away from the ice margin into the lake. The source of the diamictons may have been till emerging at the grounding line or pre-existing sediment close to the glacier margin. The interbedded layers of stratified sediment are outwash.

The trough cross-bedded and inclined sand and silt at site 37 are outwash deposited on the distal part of a subaqueous fan (Rust and Romanelli, 1975). The diamicton layers record subaqueous debris flows, probably from failures on the slope of the fan. Rip-up clasts from underlying glaciolacustrine sediments, clasts concentrated along the base, and crude bedding in one of the diamicton layers

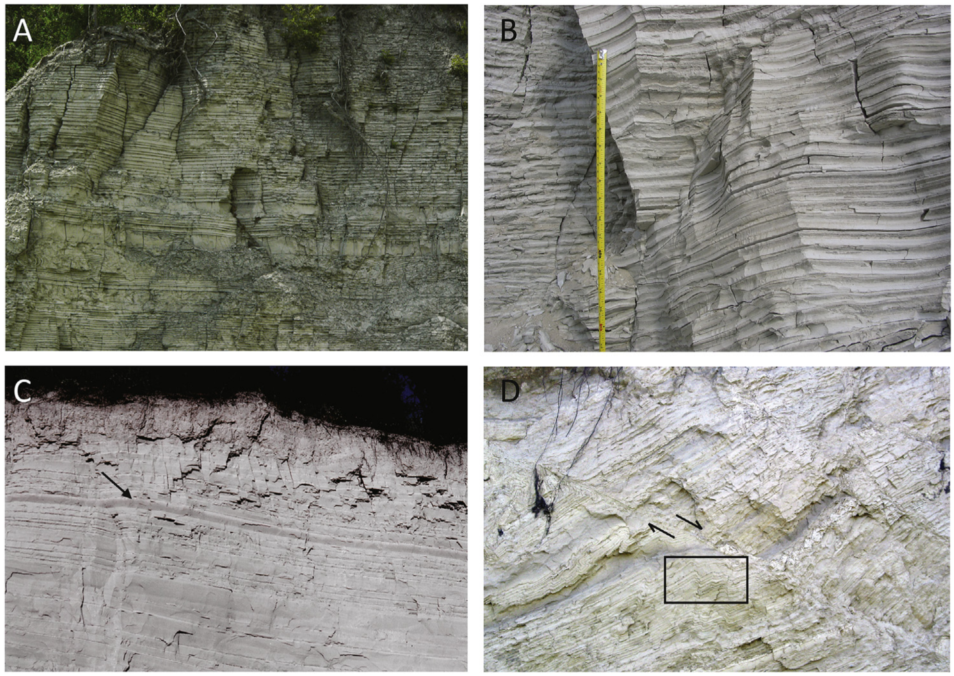


**Fig. 4.** Distal glaciolacustrine sediment. (A) An approximately 6-m-high exposure of sand, silt, and clayey silt varves. (B) Varves. Each varve comprises a massive lower layer of sandy silt and an upper thin layer of clayey silt. The exposed part of the measuring tape is approximately 45 cm long. (C) Coarse-grained varves; one conspicuous bed (arrow) was traced for several kilometres along the shoreline of Lake Roosevelt. The exposure is approximately 3 m high. (D) Faulted, folded, and tilted varves. The box highlights some of the folds. The exposure is approximately 4 m high.

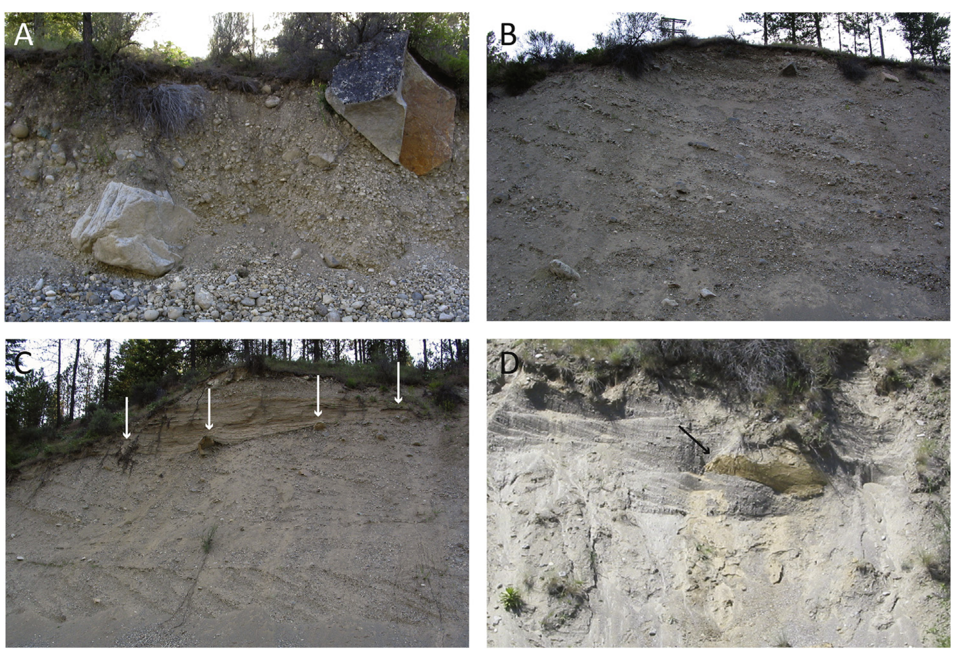


**Fig. 5.** Gravelly sediment deposited in glacial Lake Columbia by glacial Lake Missoula floodwaters. (A) Clast-supported cobble-boulder gravel with downvalley planar-inclined bedding. The exposure is approximately 5 m high. (B) Normally graded, sandy, matrix-supported pebble-cobble gravel with downvalley, planar-inclined bedding. The exposure is approximately 20 m high. (C) Normally graded, matrix-supported, pebble-cobble gravel with horizontal and downvalley, planar-inclined bedding. Note the small boulder lag at the top of the gravel sequence (arrows highlight boulders). The gravel is overlain by glaciolacustrine bedded sand and silt. The exposure is approximately 19 m high. (D) A large sandy rip-up clast (~1 m long; arrow) in trough-cross-bedded pebbly coarse sand.

indicate movement in a fluid state (Benn, 1996). The overlying upward-coarsening gravelly sand records southward progradation of the fan.

### 4.2. *Gravel-sand-silt facies association*

We documented 14 outcrops of associated gravel, sand, and silt north of Coyote Creek along the Columbia River (‘subaqueous fan sediments’, Fig. 1B). This facies association unconformably overlies diamicton or bedrock and is conformably or unconformably overlain by planar-bedded and planar-laminated sand and silt (Section 4.3).

The gravel facies are normally graded and include: clast-supported, planar-inclined, and imbricated cobble gravel (Fig. 3A); and matrix-supported, poorly to well-sorted, inclined or horizontally planar-bedded, pebble-cobble gravel with some small outsized boulders (Fig. 3A–C). Planar-inclined beds dip 8–23° downvalley (south) or cross-valley (southwest or southeast).

The gravel facies are interbedded with pebbly sand and silt facies (Fig. 3A and C). At several sites, gravel grades vertically or laterally into the finer-grained facies and the two are interbedded. These finer-grained deposits include trough and planar cross-bedded sand (Fig. 3D), horizontally planar or undulatory bedded sand (Fig. 3E), massive sand, ripple-drift cross-laminated pebbly sand, and massive silt (Fig. 3D). Most ripples indicate downvalley flow, but some suggest up- or cross-valley flow. Gravel beds or pockets of gravel and isolated outsized clasts are common within the sand (Fig. 3E). Structures such as flames, ball-and-pillows, and rip-up clasts are present but uncommon. At some exposures, these sediments are faulted and folded, and vertically laminated clastic dikes cut the strata (Fig. 3F). At other exposures the beds are steeply inclined.

At site 60, coarse gravel (Fig. 3B) is conformably overlain by a matrix-supported diamicton containing 25–30% clasts ranging from pebbles to boulders up to 30 cm in diameter. The diamicton is unconformably overlain by a 1–3 m of cobble gravel. The entire sequence is overlain by irregularly bedded sandy silt.

The gravel-sand-silt facies association records deposition on ice-marginal subaqueous fans as ice retreated up the Columbia River valley (Cheel and Rust, 1982; Paterson and Cheel, 1997; Rust and Romanelli, 1975). In Fig. 1B, the diamicton-gravel-sand facies association and the gravel-sand-silt facies association are grouped together as 'subaqueous fan sediments.' The coarsest sediments—the clast-supported gravel facies (Fig. 3A)—were deposited close to the glacier margin, possibly at the mouth of a meltwater conduit. Finer gravel (Fig. 3C) was deposited farther from the ice margin. Clast imbrication indicates transport by saltation, which implies relatively high-energy currents that are common in ice-marginal settings. The crude stratification, normal grading, local erosion, and poor sorting of the matrix-supported gravel indicate deposition by high-density cohesionless debris flows or hyperconcentrated flows (Benn, 1996). Finer gravel and sand beds (Fig. 3C) were deposited by non-channelized sheet flows moving across the fans.

Site 60 records advance and retreat of the Columbia River lobe. We infer that the lower unit is subaqueous outwash deposited in front of the glacier as it advanced southward into the lake. The gravel was overridden by the Columbia River lobe, which deposited subglacial till. As the glacier retreated, subaqueous outwash deposited a thin bed of cobble gravel on the till. Sandy silt at the top of the sequence is glaciolacustrine sediment deposited in glacial Lake Columbia (Section 4.3).

Distal slopes of the subaqueous fans are blanketed by finer grained sediments (Fig. 3D–F). Bedded and laminated sand and silt, locally with cross-beds and ripple-drift cross-laminae, record deposition from turbulent underflows. Massive sand and silt record high-concentration density underflows or suspension deposition. Current indicators indicate dominantly downvalley flow, but there is also evidence of cross-valley and upvalley flows, which is common in ice-marginal settings. The upward fining of sand and silt in this facies association indicates retreat of the ice margin upvalley. We attribute coarser lenses within the fine-grained deposits and isolated outsized clasts to ice-rafting (Fig. 3E). Faulting and folding are characteristic of ice-marginal settings where sediment becomes unstable as glaciers retreat upvalley. The clastic dykes are indicative of loading and rapid pore-water expulsion from underlying sediments.

### *4.3. Sand-silt-clay facies association*

The sand-silt-clay facies association is present throughout the study area, but is best exposed along the north-south reach of the Columbia River ('varves', Fig. 1B). It typically consists of a thick sequence of rhythmically bedded sand/silt and clayey-silt couplets (Fig. 4A and B); some exposures contain up to 300 couplets. Individual couplets range from 0.02 to 3 m thick but are commonly 2–20 cm thick (Fig. 4B). Most couplets comprise a lower layer of massive sand or sandy silt and an upper thinner layer of clayey silt (Fig. 4B). The clayey-silt layer commonly constitutes 5–20% of the couplet, but can form up to 75% of thinner couplets. Basal contacts of couplets are sharp; contacts between the sand/silt and clayey silt layers are gradational or sharp (Fig. 4B). Thicker couplets contain coarser sediment than thinner couplets (Fig. 4C), as well as microlaminations, soft-sediment deformation structures (flames and ball-and-pillows), silt/clay rip-ups, and climbing or draped ripples that indicate down- or cross-valley currents. The sand content, thickness of couplets, and frequency of current structures all increase to the north in Lake Roosevelt. Some conspicuous thicker couplets can be traced for several kilometres along the lake shore (Fig. 4C). At some exposures, rhythmically bedded sediments contain lenses of gravel with small outsized boulders. At others, the sediments are faulted or dip up to 20° (Fig. 4D).

This facies association unconformably or conformably overlies the gravel-sand-silt facies association and unconformably overlies the diamicton-gravel-sand facies association. It is overlain by postglacial sediment.

The couplets are interpreted to be varves (Ashley, 2002, 1975; Smith and Ashley, 1985). Thicker varves with a larger array of sedimentary structures are the product of high-density turbidity currents. Thinning of varves up-section indicates deepening of the lake over time, an increase in distance from the sediment source, or both. We interpret the outsized clasts and gravel lenses to be, respectively, dropstones and iceberg dumps. Deformation of the varves is attributed to destabilization of sediment when nearby or buried ice melted.

## 5. Description and interpretation of glacial Lake Missoula outburst-flood sediment

### *5.1. Gravel-sand facies association*

Sediments of the gravel-sand facies association are discontinuously exposed along a 5-km reach of the Spokane River (sites 10–14, 18, and 19; Fig. 1B). Gravel facies include unsorted to poorly sorted, clast-supported cobble gravel with outsized (up to 2 m) boulders (Fig. 5A); and unsorted to poorly sorted sandy, matrix-supported, pebble-cobble gravel with outsized (up to 2 m) boulders (Fig. 5B). Individual beds range up to 2 m thick and are commonly normally graded (Fig. 5B and C), but a few beds are reversely graded or massive. Contacts between beds are conformable or erosive. Boulder or cobble lags are present at the top of many of the gravel beds (sites 13, 14; Fig. 5C). Gravel beds are planar and either horizontal or inclined up to 35° downvalley (Fig. 5A–C). Trough cross-bedding was noted at a few sites (Fig. 5D). Most gravel clasts are subrounded, but some are subangular to angular. More than half of the clasts are argillite, quartzite, or other metamorphic rocks of the Precambrian Belt–Purcell Supergroup. Other lithologies include granitic rocks, vein quartz, and gneiss. Gravel beds contain rip-ups of sand, silt, or clay up to 2 m long (Fig. 5D); small

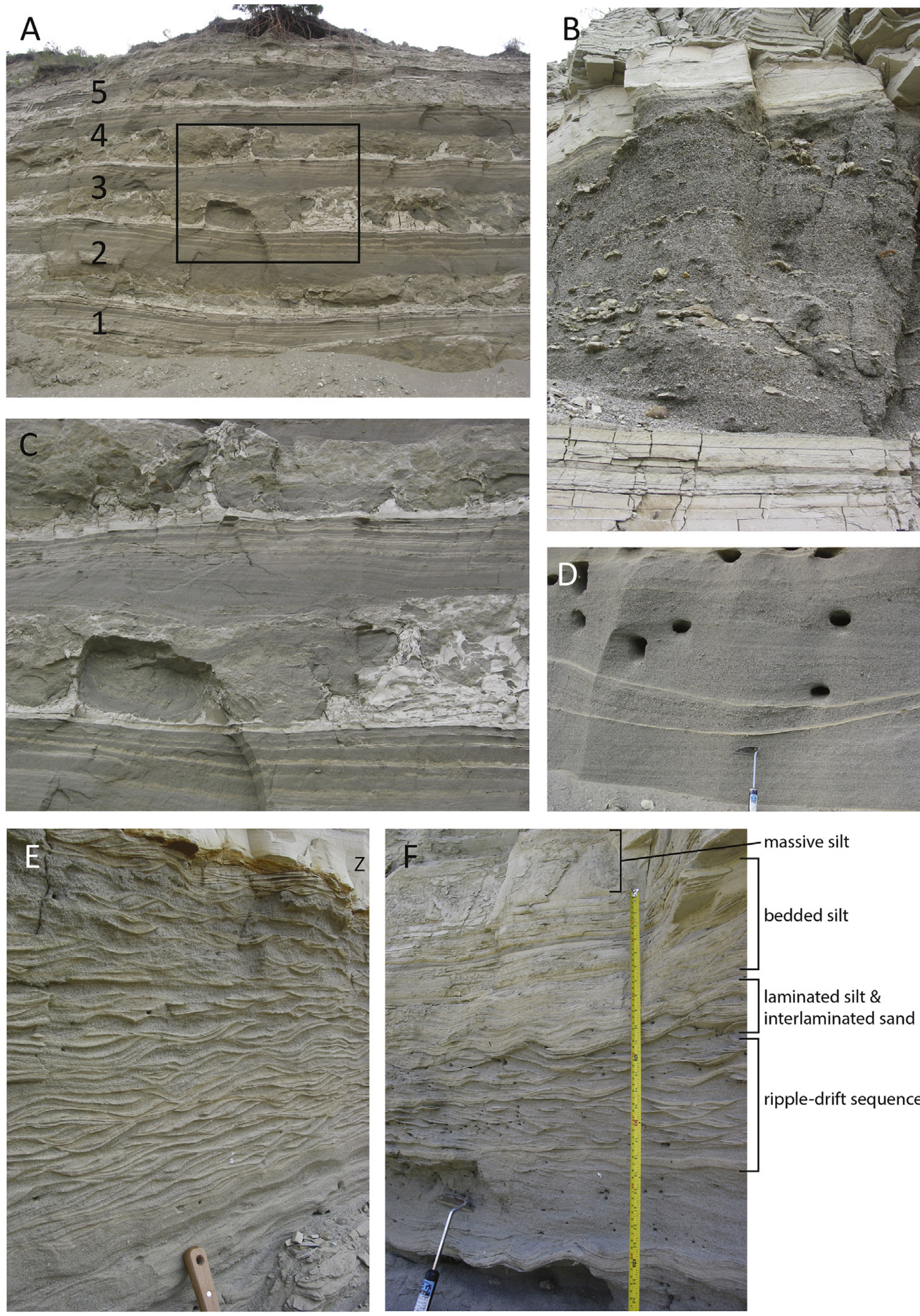


**Fig. 6.** Examples of sand and silt deposited in glacial Lake Columbia by glacial Lake Missoula floodwaters. (A) Five sand flood units bounded by silty varves near Hawk Creek. Flood units have loaded lower contacts, silt rip-ups, planar beds, and massive beds. Box highlights photo C. (B) A pebbly coarse sand flood bed at Hawk Creek (site HC). The flood bed has an erosive planar lower contact, contains beds with abundant silt rip-ups, and is sharply overlain by laminated silt. (C) Close-up of part of photo A. The flood unit has a loaded lower contact and silt diapirs and silt rip-ups in the lower part of the unit. The flood unit grades upward into planar-bedded sand and silt. The entire sequence is draped by silty varves that were loaded and eroded by a subsequent flood. (D) Trough cross-beds in a flood unit with laminae of silt at the base. The tool is 26.5 cm long. (E) Climbing ripple-drift sequence sharply overlain by laminated silt (Z). (F) Climbing ripple-drift sequence grading upward into laminated silt and interlaminated sand, which is overlain by bedded and massive silt (displayed portion of tape is ~70 cm).

rip-ups tend to concentrate in specific beds. Interbeds of massive pebbly coarse sand or silt are present within the gravel. At a few sites, the gravel fines upward through the entire exposure. The gravel fines downvalley to the northwest along the Spokane River from poorly sorted, matrix-supported, pebble-cobble gravel to coarse pebbly sand. The gravel-sand facies association underlies the finer-grained facies association described in Section 5.2.

The gravel-sand facies association was deposited by glacial Lake Missoula floodwaters as they flowed through glacial Lake Columbia. The sediments are similar to those deposited on flood expansion bars and include: clast-supported gravel indicative of deposition from high-energy traction carpets; poor sorting and crude stratification reflecting deposition from turbulent flow with a high sediment load; and large-scale planar beds and cross-beds indicative of deposition from sheets of bedload on a downstream-migrating bar (Baker, 1973; Maizels, 1997; O'Connor, 1993). We attribute inverse grading in some beds to grain collisions in a hyperconcentrated flow whereby coarser grains move to zones of lower shear at the edges of the flow (Baker, 1973; Maizels, 1997, 1989) or to increasing flow velocity and sediment availability during the waxing stage of a flood (Maizels, 1997). The decrease in sediment size up-section and downstream indicates a decrease in flow and is characteristic of flood bars, particularly expansion bars. Most clasts are sub-rounded, but some are angular, which indicates local entrainment of clasts, possibly due to erosion or collapse of nearby bedrock. The boulder lags developed by winnowing of the surface of the bar during waning stages of flow (Baker, 1973; Maizels, 1997; O'Connor, 1993; Rushmer, 2006; Russell, 2007). Rip-up clasts were eroded from interflood glaciolacustrine sand and silt. The ~2-km-wide, ~7-km-long expansion bar that hosts the gravel-sand facies association was deposited where floodwaters decelerated as they flowed out of a constriction and expanded to the northwest (Fig. 1B). The bar abuts bedrock along the western side of the lake. The large scale of the gravel foresets suggests that this bar was deposited during the early or maximum stage of a flood (Rushmer, 2006).

### 5.2. Sand-silt facies association

The sand-silt facies association crops out along much of the shoreline of Lake Roosevelt (Fig. 1B). 'Units', which we interpret to be sand and silt deposited during a single event, range from a few centimetres to ~5 m thick, but are commonly between 0.5 m and 2 m thick. Units generally thin up-section and in the down-flow direction. Numerous units are commonly exposed at most sites, interbedded with the distal glaciolacustrine sediments (Fig. 6A). The maximum number of units at any one site is 37 exposed over a 96.5-m-thick section at Hawk Creek (site HC, Fig. 1B). Based on the thickness of exposed units, we estimate that six to nine more units are covered by colluvium in the lower part of the Hawk Creek section.

Fig. 7 is a schematic drawing of two typical units of the sand-silt facies association separated by glacial Lake Columbia varves. Units, including those shown in Fig. 7, are normally graded, ranging from cobbly to pebbly very coarse sand at the base to silt at the top. The contact between a unit and underlying varves is loaded (Figs. 6A and 7), planar (Figs. 6B and 7), undulatory, and erosive. Varved sediments separating successive units range from a few centimetres to 2 m thick (Fig. 6B and C). In some cases, varves are discontinuous or missing between two units, having been eroded. The number of varves between sand-silt units could not be counted at every site, but where counted, range from three to 87. Some units have loaded the underlying varves, producing flame structures and diapirs up to 2.5 m high (Fig. 6A and C). Silt rip-ups are common in the lower part of units and can have the form of stringers <10 cm thick up to 1.5 m long (Fig. 6A–C). Dish structures, pillow structures, and micro-faults are less common.

The base of some units is massive and poorly sorted sand. Above this massive zone is planar- or laminated bedded sand (Fig. 6C), followed by planar- or trough cross-bedded sand (Fig. 6D), then climbing ripple-drift sand that grades from type-A and type-B ripples to draped ripples (Fig. 6E), locally with flame structures and pillows. Above this is laminated silt and minor rippled sand (Fig. 6F) capped by one to several massive silt beds that have a combined thickness of ≤1 m and are slightly pink (Figs. 6F, 8A and 8B). The massive silt beds are most common along the upper

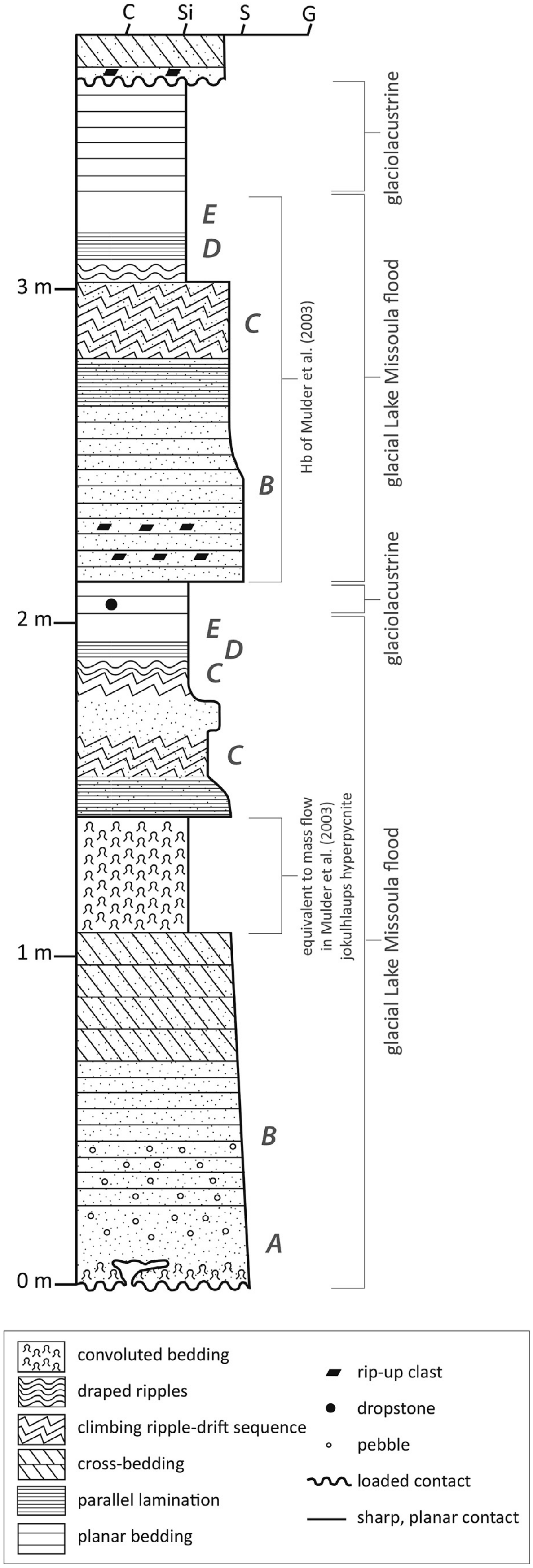


**Fig. 7.** Schematic drawing of two typical glacial Lake Missoula sand and silt flood units separated by glacial Lake Columbia varves. Not all flood units contain every characteristic depicted here. Italicized letters represent traditional turbidite sequence units.

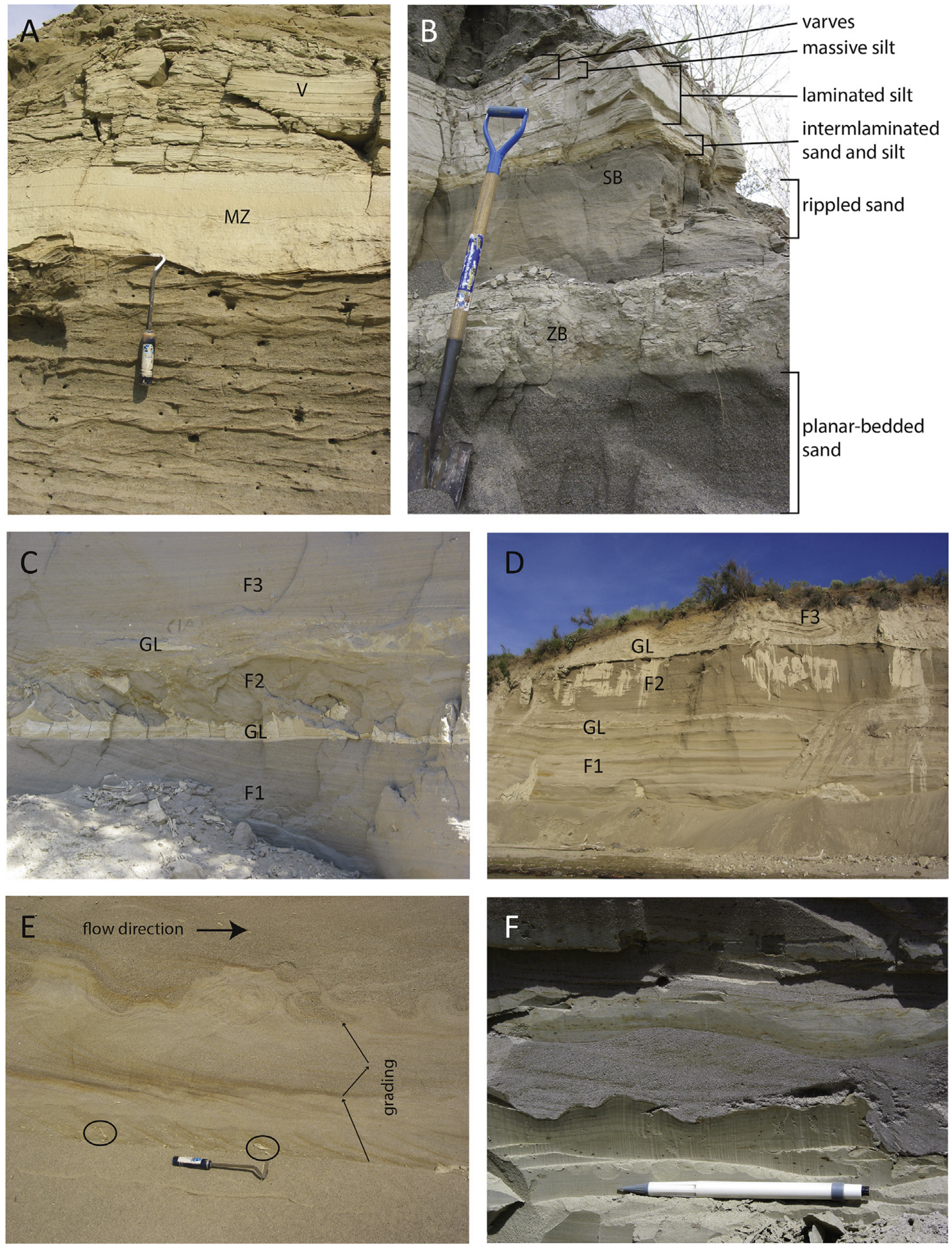


**Fig. 8.** Glacial Lake Missoula sand and silt flood units in glacial Lake Columbia. (A) Sandy climbing ripples in a flood bed (site HC). The flood bed is sharply overlain by massive silt (MZ), which grades upward into silty varves (V). The tool is 26.5 cm long. (B) An upward-fining flood bed (site HC). Planar-bedded sand grades upward successively though rippled sand, interlaminated sand and silt, laminated silt, and massive silt into silty varves. The sequence is interrupted by a massive, brecciated silt bed (ZB) and a massive, reverse-graded sand bed (SB). The shovel is ~1 m long. (C) Three sand flood beds (F1, F2, and F3) separated by thin loaded varved silt (GL). The fine-grained flood facies are absent at this site. (D) Three flood beds (F1, F2, and F3) separated by varves (GL) (site 91). The lower flood bed comprises approximately 15 sand beds. (E) Close-up view of two beds in photo D. The lower bed contains normal and reverse grading (arrows), cross-beds, and silt rip-ups (circles). Flame structures at the top of the bed are attributed to loading by the overlying coarser sand bed. (F) One of the four anomalous beds at site 67. The bed has an erosive lower contact, type-A ripples indicating upvalley flow (to the left), and a pinkish colour different from that of the bounding varves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Columbia River, Sanpoil River, and Hawk Creek. They are conformably overlain by varves (Figs. 7, 8A and 8B).

There are exceptions to the common sequence of sediments in units, as described above. Some units include reversely graded beds with gradational basal and upper contacts (Figs. 7 and 8B). Some units contain massive, brecciated or convoluted beds of finer-grained material within the overall fining-up sequence (Figs. 7 and 8B). Others have inset channel fills comprising massive, clast-supported, cobble-boulder gravel with angular to sub-angular clasts.

Along the Spokane River and the Columbia River below the Spokane–Columbia River confluence, uncommonly thick units, up to 5 m thick, contain planar-bedded or cross-bedded, pebbly coarse sand with sharp upper and lower contacts and rip-up clasts; the finer-grained facies are absent (Fig. 8C). These units are unconformably overlain by either massive silt beds or silty varves (Fig. 8C).

Sand-silt units at sites 7 and 91 (Fig. 8D) contain an uncharacteristically large number (6–15) of beds. The beds are massive or normally graded, but can be reversely graded in the middle (Fig. 8E). They contain laminations, cross-beds, or ripples, and commonly load underlying beds, producing rip-ups and flame structures oriented down-flow (Fig. 8E). Some of these beds thin in the down-flow direction.

Ripples and cross-beds in sand-silt units exposed along the Spokane River and the Columbia River below the Spokane–Columbia river confluence indicate downvalley flow. In exposures along the upper Columbia River and Sanpoil River, ripples, cross-beds, flame structures, and rip-up stringers indicate both up- and downvalley flow. Where only downvalley ripples are present, they are common only in the upper part of the unit. In the Sanpoil Valley, two dominant paleocurrent directions were noted in the same units, with downvalley ripples above upvalley ripples, cross-beds, or flame structures (Atwater, 1986; e.g., site SP-8, Fig. 1B). Most ripples in the Hawk Creek embayment indicate cross-valley flow in both directions or downvalley flow towards the Columbia River. There are two exceptions to these current directions: below the Sanpoil River, two exposures (sites WLR-1 and WLR-2; Fig. 1B) include cross-bedded, cobbly to pebbly coarse sand inclined toward the east (upvalley).

One to four anomalous sand beds were noted in five, closely spaced exposures dominated by varves (sites 65–69, Fig. 1B), ~33 km north of the Columbia–Spokane river confluence. The beds are 4–37 cm thick, much thicker than the bounding varves and have either an erosive or loaded basal contact (Fig. 8F). They comprise type-A (Fig. 8F) or type-B rippled fine to medium sand, which is not present in the bounding varves, and are draped by fining-upward sand, silt, and clay. At the site with four anomalous sand beds (site 67, Fig. 1B), the ripples in three of the beds indicate upvalley flow; ripples in the second lowest bed indicate downvalley flow. The sand has a pink tinge that contrasts markedly with the olive grey colour of the bounding sediment (Fig. 8F). The sand beds can be traced over a distance of 3 km and are separated by 97–152 cm of silt and clayey silt.

The sand-silt association was deposited by glacial Lake Missoula floodwaters. The flood units were deposited by a continuum of discharges and flow velocities, but can be divided into two groups: those along the main path of the Missoula floods that travelled generally westward through glacial Lake Columbia; and those in back-flooded tributary valleys such as the upper Columbia River, Hawk Creek, and the Sanpoil River.

The east–west reach of glacial Lake Columbia contains exposures of the flood gravel-sand facies association but is dominated by outcrops of the flood sand-silt facies association (Fig. 1B), in particular, the up-to-5-m-thick units that lack the finer-grained facies and that are unconformably overlain by massive silt or silty varves (Fig. 8C). Loaded lower contacts and rip-up clasts indicate that these sediments were likely deposited during early rising or maximum stages of floods. The unconformable upper contact indicates that either flow velocities were high enough to prevent deposition of the finer facies or that the upper part of the flood deposits was eroded before the silt was deposited. It is likely that some floods eroded, not only the underlying varves, but also the underlying deposits of one or more floods. At one location in Sanpoil Valley, Atwater (1986) observed that a flood eroded at least three varved units and their intervening flood beds.

The upvalley cross-beds at two exposures (sites WLR-1 and WLR-2, Fig. 1B) are anomalous. This counterintuitive flow direction might be due to upvalley flow after floodwaters encountered the Okanogan lobe that dammed glacial Lake Columbia. Two units at site WLR-2 indicate that, if true, this occurred during more than one flood. The coarseness of the sediment—cobbly to pebbly coarse sand—and the distance traveled from the ice dam (~15 km) indicate that these floods were likely earlier, larger floods.

Preserved flood beds in the back-flooded channels (Hawk Creek, upper Columbia River, and the Sanpoil River valley) were deposited by currents with lower velocities that resulted in preservation of more of the intervening varves. The presence and preservation of the finer-grained facies of these units are also consistent with deposition in calmer arms of the lake. The flood units described in these back-flooded channels are similar to glacial Lake Missoula flood beds in glacial Lake Columbia described by Atwater (1987, 1986, 1984) and Waitt (1985, 1984): (1) the flood units rest across erosional contacts on underlying varves or flood beds, or are convoluted with the underlying varves; (2) the base of some units contains rip-up clasts from underlying varves; (3) units are normally graded from granule gravel or coarse sand to silt or clay; (4) lower parts of the units consist of planar-laminated sand, in some instances with outlier cobbles or boulders; (5) planar laminations are succeeded upward by rippled sand that in the lower parts of units in tributary valleys indicate upvalley flow, and in the middle and upper parts of units indicate downvalley flow; (6) ripples are overlain by draped, planar-laminated, and massive very fine sand or silt; (7) the uppermost parts of the units consist of normally graded or massive silt or clay that sharply overlies sand; (8) the graded or massive silt at the top of some units grades into varves; (9) some of the fine-grained sediment is pink in colour, unlike adjacent varves; and (10) flood units thin and fine up-section. These units are also similar sedimentologically to the subaerially deposited glacial Lake Missoula back-flooded, slackwater rhythmites of the Touchet Beds in southern Washington (Atwater, 1984; Waitt, 1985).

Erosion of underlying sediment and the widespread occurrence of rip-up clasts attest to the high energy involved in deposition of the flood sediments. Planar bedding at the base of flood units is indicative of the upper flow regime and possibly the waxing phase of the flood. The vertical sequence of the rippled bedforms indicates very rapid sedimentation and lower energy flows during waning of the flood. Draped and laminated silt near the top of flood units was deposited from suspension in the lower flow regime, but the presence of interbeds of sand indicates fluctuating flow. Once the turbulent floodwaters had passed, the silt in the water column settled out, producing the massive silt beds. These silt beds were likely deposited over the days to months following the flood. For example, it would have taken eight to 22 months for fine particles in the water column to reach the lake floor at Manila Creek, assuming that the surface of glacial Lake Columbia was 715 m above sea level (asl) at its highest stand (not flood swollen), that the lake floor was between 457 and 502 m asl at Manila Creek (Atwater, 1986), and that silt-to clay-sized particles (4.5–3 μm) settle at a rate of 0.27–0.62 mm/min Atwater (1983) and Waitt (1984) also concluded that these silt beds are part of the flood-laid unit, deposited before the return to normal glaciolacustrine sedimentation.

Differences between the flood beds described here and those described by Atwater and Waitt include: (1) an absence of reverse grading in the lowest part of the flood units, which was noted by Atwater (1987) and Waitt (1984) in flood beds deposited in glacial Lake Priest, Idaho, and by Atwater (1987) at the Steamboat Rock exposure in Grand Coulee; (2) some of the units described here have massive, poorly sorted sand at their base; and (3) two of the units have numerous beds.

Atwater (1987) and Waitt (1984) attributed reverse grading at the base of flood units to deposition during the waxing part of the flow. Reverse grading was noted at some of the sites described here, but we attribute the finer sediments at the base of the flood units to sand being mixed with silt and clay eroded from the underlying varves, because these parts of the units are dominated by convolute bedding, diapirs, and silt rip-ups (Fig. 6A and C). The absence of true reverse grading at our sites is likely due to: (1) high-energy floodwaters eroding earlier-deposited sediments; (2) ice dam tunnels enlarging rapidly enough that the peak discharge caught up

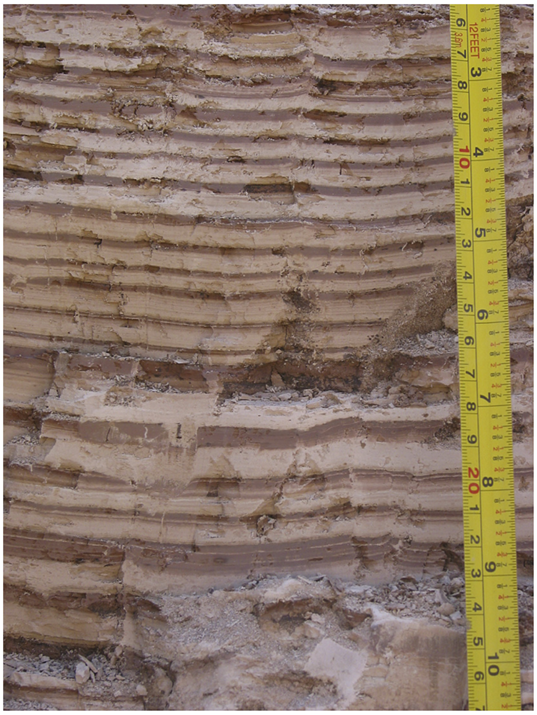

**Fig. 9.** Glacial Lake Missoula bottom sediment, displaying 22 varves. The pink tinge is attributable to Belt–Purcell Supergroup rocks in the glacial Lake Missoula basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the lesser earlier discharges by the time floodwaters entered glacial Lake Columbia (Atwater, 1986); or (3) indirect flood pathways, such that the waxing part of the flood hydrograph is not present at all sites. The latter two explanations are favoured at sites where loading of the underlying silt and rip-up clasts are present because there is no evidence of erosion of coarser flood sediments. The waxing or peak phase of the flood may be recorded, however, at sites where there is a massive, poorly sorted sand bed at the base of a unit. These beds could reflect large sediment concentrations and insufficient time for the sediment to become sorted or graded while it was being deposited (Maizels, 1997; Rushmer, 2006).

The anomalous number of beds in a few of the flood units (sites 7 and 91; Fig. 8D and E) are likely the product of velocity pulsing of turbulent flows within a single flood, something that has been described in Icelandic jökulhlaups (Maizels, 1989; Russell and Knudsen, 1999). A steady underflow can transform into an unsteady, non-uniform current, and thus bed shear stresses and sediment entrainment and deposition would vary during a flood (Best et al., 2005). Non-uniform flow could produce beds of different grain sizes, loading of underlying beds, and the variety of sedimentary structures seen in individual beds within one flood unit. Sites 7 and 91 are in the east–west reach of the lake and are not overlain by the ripple-drift sequence found in the back-flooded valleys. These numerous beds are possibly equivalent to other sand-silt facies association sediments in the east–west reach and therefore were likely deposited by high flow during waxing and early waning flood stages.

The massive, brecciated, or convoluted beds of finer-grained sediment that interrupt the fining-upward sequence of a flood unit (Figs. 7 and 8B) are attributed to mass flows triggered by the floodwaters during waning flow stages. Any mass movement triggered by waxing or peak flows probably would have been entrained in the flood waters and not deposited locally. Because a mass flow would move slower than the turbulent current that it is moving through, its deposit lies within the fining-upward sequence. We attribute the channelized, clast-supported cobble-boulder deposits to mass wasting from nearby bedrock that was destabilized by the floodwaters.

## 6. Chronology

Delicate detrital plant tissue was collected from bedded silt at the base of the 96.5-m-high section at Hawk Creek (site HC, Fig. 1B). The sample was collected from an intact block of silt directly below the exposure. Because it was intact, we assumed that the block had not traveled far, and therefore we associated it with varves immediately below all 37 flood units logged at the site. The sample yielded an age of 13,400 ± 100 $^{14}$C BP (Beta-225100).

## 7. Discussion

### *7.1. Source of flood sediments in glacial Lake Columbia*

Atwater (1987, 1986, 1984) and Waitt (1984) have previously described glacial Lake Missoula flood sediments in glacial Lake Columbia. Not all researchers, however, have been convinced of glacial Lake Missoula's influence on glacial Lake Columbia. Shaw et al. (1999) discussed one of Atwater's (1986) Sanpoil Valley sites (Sage Trig) and argued against glacial Lake Missoula flooding and in favour of outburst floods from beneath the Cordilleran ice sheet to the north. They concluded that floods from the north were responsible for gravel and sand cross-beds, diapiric injections of silt and clay into overlying gravelly sand, glaciolacustrine rip-up clasts, and soft-sediment deformation structures. They overlooked, however, the implication of the fact that Atwater documented flow to the east-northeast at that site, as well as flow to the north at four sites farther north in Sanpoil Valley. Similarly, Peters (2003) and Peters et al. (2002) described two exposures of gravel foresets in the lower Spokane River valley (our sites 11–14, 18, and 19) and upper Columbia River valley (our site 60), respectively, which they interpret as evidence of floods from sources other than glacial Lake Missoula. We interpret these exposures, respectively, as part of a flood expansion bar (Section 5.1) and a proglacial subaqueous outwash sequence (Section 4.2). Gaylord et al. (2007) confirmed, using detrital zircon geochronology, that stratigraphically low flood beds in the Sanpoil River valley record floods from glacial Lake Missoula. However, they attributed stratigraphically higher flood beds (not specifically identified) to meltwater from the retreating Cordilleran ice sheet, thus implying that not all of Atwater's 89 beds can be attributed to glacial Lake Missoula flooding. Using magnetic properties of fine-grained sediments, Hanson et al. (2015) also confirmed a glacial Lake Missoula source for some of the beds in the Sanpoil River valley.

We found no evidence of large-scale flooding from the north at the sites that we studied, although we cannot conclusively rule it out. Evidence supporting a glacial Lake Missoula source for the flood beds in western glacial Lake Columbia includes: (1) current indicators; (2) the areal distribution of flood beds; (3) clast lithology; and (4) the colour of some of the fine-grained sediments. Nearly all current structures indicate flow of floodwaters from east to west in the lake, clearly demonstrating a glacial Lake Missoula source. Anomalous current indicators (sites WLR-1 and -2) have been addressed (Section 5.2) and cannot conclusively be attributed to flooding from a source other than glacial Lake Missoula. Current structures also indicate northward flow up tributary valleys; where present, southward current indicators commonly overlie northward indicators within the same bed, reflecting flow back down-valley after the upvalley surge. In the Columbia River valley, flood beds are not found north of site 66 (Fig. 1B); exposures to the north are dominated by varved sediments and do not contain evidence of large-scale flooding down the Columbia River. Gravel samples from the expansion bar in the Spokane River (sites 10–14, 18, and 19) indicate a dominance of clasts from the Belt–Purcell Supergroup, which is the bedrock surrounding the glacial Lake Missoula basin and is not present in Washington or to the north of glacial Lake Columbia, emphasizing a glacial Lake Missoula origin for the flood that deposited that bedform. Lastly, the pinkish tinge of the sand and silt in the upper part of the sand-silt flood association is reflective of the colour of the lake bottom sediments of glacial Lake Missoula (Fig. 9).

### 7.2. *Flood sediments as turbidites*

The sequence of sedimentary structures in the flood sand-silt facies association is similar in many respects to a classic turbidite (Baker, 1973; Bjornstad, 1980; Bretz et al., 1956; Bunker, 1982; Waitt, 1985, 1980), which is characterised by an upward sequence of massive medium sand, planar laminated fine-medium sand, ripple laminated fine sand, parallel laminated silt, and massive clay (Fig. 7). There is at least one significant difference, however, between turbidites and these flood sediments: the processes by which turbidites are deposited.

Turbidity currents commonly occur in response to a triggering event, such as an earthquake- or storm-induced landslide (Mulder et al., 2003). They are characterised by highly turbid water with large amounts of suspended sediment that increase in density as they flow downward through less dense water in marine environments. This process differs from the passage of sediment-laden flood through a relatively shallow lake. Mulder et al. (2009, 2003) have shown, however, that a type of turbidity current (hyperpycnal surge) can form when a flood with a sufficiently high sediment concentration enters a standing body of water. Indeed, Zuffa et al. (2000) attribute deposition of beds of glacial Lake Missoula origin, >1100 km from the mouth of the Columbia River, to hyperpycnal gravity flows. These quasi-steady flows can last hours to weeks and contain very high sediment concentrations.

Mulder et al. (2003) describe a hyperpycnite sequence caused by a glacial outburst flood. During the waxing stage of the flood, the flow deposits a coarsening-upward basal unit (Ha), whereas during the waning stage, the flow deposits a fining-upward unit (Hb, Fig. 7), commonly with climbing ripples, parallel and cross-bedding, and intrasequence erosional contacts. Mass flows can form simultaneously with the hyperpycnal surge, and their deposits can be intercalated with the hyperpycnite or superimposed on it (Figs. 7 and 8B). A complete hyperpycnite would consist of both the coarsening and fining sequences, and the transition between the two would correspond to the maximum grain size and the peak discharge of the flood (Mulder et al., 2003). Mulder et al. (2003) suggest that complete hyperpycnite sequences may be rare in the stratigraphic record because discharge and velocity at flood peaks are high enough to erode previously deposited sediments, a scenario that likely existed in glacial Lake Columbia. Based on this description, we thus conclude that the sand-silt facies association in glacial Lake Columbia is composed of incomplete hyperpycnite sequences.

### 7.3. *Characteristics of glacial Lake Missoula flooding in glacial Lake Columbia*

Glacial Lake Columbia was clearly a dynamic environment, subject to frequent, high-magnitude outburst floods from glacial Lake Missoula. The characteristics of the flood sediments within glacial Lake Columbia are dependent on several factors: the magnitude and frequency of the floods; the shape of the flood hydrograph; the abundance of entrainable material, and the geometry of the lake.

Flood magnitude is dependent on the volume of water in glacial Lake Missoula (≤2600 km$^3$; Smith, 2006), which itself depends on the thickness of the ice dam. As the Purcell Trench lobe began to retreat, the ice dam became thinner between successive floods, impounding less water each time and flooding more frequently (Atwater, 1986; Waitt, 1985). At the Manila Creek composite section, Atwater (1986) noted an overall decrease in the thickness, maximum grain size, and erosiveness of the flood beds up-section, and a coincident decrease in the number of varves between flood beds, all of which reflect changes in the magnitude and frequency of glacial Lake Missoula flooding. Although none of our exposures is as comprehensive as Atwater's, we noted similar trends at many sites, mostly in the back-flooded valleys.

Evidence of the higher-energy floods is evident in the grain-size (boulders and cobbles) of some of the flood beds (e.g., the expansion bar along Spokane River) and the erosiveness of the floodwaters, with very little, or nothing, left of the interbedded varves in the east–west reach of the lake. The Spokane River expansion bar represents the largest glacial Lake Missoula flood recorded in western glacial Lake Columbia. This landform, however, does not compare in size to some of the landforms in the Channeled Scablands (Baker, 1973). It could be that much of the record of glacial Lake Missoula flooding in glacial Lake Columbia is not exposed or that many of the earlier floods were eroded by subsequent floods with higher flows.

The coarser facies of the sand-silt flood facies association present in the east–west reach also represent high-magnitude flood events, although smaller than the flood that created the expansion bar. The shortness of the flood record in these areas is consistent with high energy, highly erosive floods. These high-magnitude flood events of short duration dominate the sedimentary record, representing nearly 100% of the sediment in exposures. In the back-flooded valleys, the sedimentary record is more complete because of the relatively calmer nature of these environments.

The four sand beds 33 km upvalley from the Columbia–Spokane River confluence are the most northern distal glacial Lake Missoula flood deposits in glacial Lake Columbia and thus are likely associated with large flood events, at least while the Columbia River lobe was not fully advanced. It is not certain that these four sand beds record four individual floods. It is difficult to estimate the time between these beds based on the silt between them. The best estimate is that, at most, three varves were deposited between two of the beds, which is inconsistent with what is known about the timing of glacial Lake Missoula floods. Atwater (1986) counted 1–20 varves between the last 17 floods, which he attributed to a decrease in the period between floods as the ice dam thinned toward the end of the Fraser Glaciation. This scenario is not compatible with the interpretation that the four sand beds are products of larger floods because they would have occurred earlier in the flooding sequence than the ones in the Sanpoil Valley that have few varves between them. It is possible that there are no varves between these four beds and that the beds are the product of a single flood, with intermittent surging or pulsing. In this scenario, the second bed with the downvalley ripples would record the recession of floodwater during one surge and the bedded to massive silt could be deposited rapidly from high-concentration sediment flows between pulses.

Changes in the ice dam over time would affect the shape of the flood hydrograph. A typical glacial outburst flood hydrograph commonly exhibits a prolonged rising limb followed by a rapid falling limb, reflecting gradual expansion of tunnels until the lake has drained to the level of the tunnels (Carling, 2013; Maizels, 1997). But most hydrographs will also exhibit irregularities caused by temporary blockages in the ice dam and floodway paths, differential expansion rates of ice tunnels, access to en- or subglacial water storage, and/or different flood paths, all of which can cause separate flood waves or pulsed hydrographs (Carling, 2013; Maizels, 1997, 1993). Furthermore, it is possible that the lake drained due to mechanical collapse of the dam, rather than enlargement of subglacial tunnels. In any case, by the time the floodwaters reached the eastern edge of the study area, they had travelled ~100 km from the ice dam, largely through eastern glacial Lake Columbia and likely following multiple pathways. Thus it is not reasonable to assume that the flood hydrograph would still have its original shape. The absence of reverse grading in all of the units observed, or why there is very little record of the waxing or peak surge in the sediments, could be explained by the peak surge catching up to the initial flood surge. Erosion by the peak flood surge could also explain the lack of reversely graded deposits. Because reverse grading is so noticeably absent, and, in many cases, interflood sediment is preserved and loaded, we prefer the former explanation.

Because glacial Lake Missoula floods were large and occurred in a glacial environment, sediment availability was not likely an issue. Earlier floods likely had access to more glacially derived sediment than later floods, but later floods had more access to glaciolacustrine sediment in both glacial lakes Missoula and Columbia. In Manila Creek, for example, flood sediments appear to be dominated by locally derived glaciolacustrine sediment with only a small contribution of glacial Lake Missoula sediments (Hanson et al., 2015).

The division of glacial Lake Columbia into relatively narrow, east–west and north-south reaches clearly affected the distribution and characteristics of the flood sediments. The narrowness of the lake reaches would have had increased flow depths and thus shear stress, producing greater flood power and higher transport and erosive capacities. This result is evident in the east–west reaches, which have the largest calibre sediment and where very little interflood sediment has been preserved. When floods flowed up the tributaries, shear stress, flood power, and thus transport and erosive capacities decreased, allowing for more preservation of interflood varves and flood beds.

### 7.4. Chronology

Chronological control on glacial Lake Columbia and the advance and retreat of the Okanogan, Columbia River, and Purcell Trench lobes of the Cordilleran ice sheet is poor. An age of 17,240 ± 330 $^{14}$C yr BP on a piece of wood approximately 100 km north of the ice limit is a maximum age for the advance of the Columbia River lobe into Washington (Clague et al., 1980). Using varve counts and a radiocarbon age of 14,490 ± 290 $^{14}$C yr BP on a piece of wood recovered from a varve at Manila Creek, Atwater (1986) estimated that the Okanogan lobe dammed the Columbia River from shortly before 15,550 ± 450 $^{14}$C yr BP to approximately 13,050 ± 650 $^{14}$C yr BP. The presence of Glacier Peak tephra G in the lowermost 20 km of the Okanogan Valley, Washington, indicates that the Okanogan lobe had retreated 80 km from its maximum position at the Withrow moraine, had left the Columbia River valley, and no longer dammed glacial Lake Columbia before 11,600 ± 50 $^{14}$C yr BP (Kuehn et al., 2009, and references therein; Porter, 1978).

The new radiocarbon age from this study (13.4 ± 0.1 $^{14}$C ka BP) fits well with what is known of the chronology of glacial Lake Columbia. At least 37 glacial Lake Missoula flood units overlie the glaciolacustrine sediment from which the dated sample came. This age indicates that these flood beds were deposited later in the sequence of glacial Lake Missoula flooding, and thus represent some of the smaller floods that were produced by a thinning Purcell Trench lobe.

Because of the erosive nature of the floodwaters at this site, numbers of varves between flood units are low, commonly less than 10, thus it is difficult to estimate the total time spanned by the exposure. Estimates on the recurrence interval of glacial Lake Missoula floods range from a minimum of 20 to a maximum of 107 years (Atwater, 1986; Hanson, 2013; Levish, 1997; MacEachern and Roberts, 2013; Waitt, 1985, 1984). A correlation based on paleomagnetic secular variation of glacial Lake Missoula flood sediments deposited in glacial Lake Columbia (Hanson, 2013) provides an average recurrence interval of 55 years, which is consistent with varve counts at other locations in glacial Lake Columbia where floodwaters were less erosive (Atwater, 1986; Waitt, 1985, 1984). At Manila Creek, however, Atwater (1986) reported an upward decrease in numbers of varves between glacial Lake Missoula flood units, thus 55 years is probably not appropriate for flood beds in the upper part of the Hawk Creek exposure. MacEachern and Roberts (2013) estimated a tetrapod-recolonization time between some of the later floods in southern Washington to be about 20–30 years. An estimated recurrence interval of 25 years, applied to the entire section, means that the exposure might span ~900–1150 years, depending on the number of flood units covered by colluvium. By this line of reasoning, we produce an age of 12.2–12.5 ± 0.1 $^{14}$C ka BP for the top of the exposure and presumably the end of glacial Lake Missoula flooding into glacial Lake Columbia. At Manila Creek and the Steamboat Rock section in the Upper Grand Coulee, decades to centuries of varved sediment were deposited after the last glacial Lake Missoula flood, indicating that the Purcell Trench lobe that dammed glacial Lake Missoula started to retreat before the Okanogan lobe, which dammed glacial Lake Columbia (Atwater, 1986; Waitt et al., 2009). These sediments are not present at the top of the Hawk Creek exposure, but the estimated age of the top of the exposure is within two sigma of Atwater's estimate for the retreat of the Okanogan lobe and is consistent with retreat of this lobe based on the Glacier Peak tephra G age.

## 8. Conclusions

Sediments deposited by outburst floods dominate the sediment fill in western glacial Lake Columbia. We established the source of the floods to be outbursts of glacial Lake Missoula based on: current indicators (east to west in the main part of the lake, and up and then down tributary valleys); Belt–Purcell Supergroup clasts; the pink colour of silt associated with glacial Lake Missoula lake bottom sediments; and the absence of flood sediments in the northern reach of the lake. Although we found no evidence for flooding from another source into glacial Lake Columbia, we cannot conclusively rule it out.

The east–west reach of glacial Lake Columbia is dominated by coarse flood facies, including a flood expansion bar. The rarity of intervening glaciolacustrine sediment along this reach indicate that the floodwaters were very erosive. The north-south reaches of the lake are dominated by back-flooded sediment. Sedimentary structures and thicker beds of varves between floods indicate that these reaches were calmer and less subject to erosion by floods than the east–west reach. The sand-silt flood facies association is very similar to flood sediments described elsewhere in glacial Lake Columbia and to slackwater sediments deposited by glacial Lake Missoula floodwaters in southern Washington. These fine-grained sediments show some similarities to classic turbidite sequences, but here are classified as deposits of hyperpycnal flows, a specific type of turbidity current.

The timing of later, smaller floods from glacial Lake Missoula into glacial Lake Columbia is constrained by a radiocarbon age on plant detritus of 13.4 ± 0.1 $^{14}$C ka BP. The dated sediment is overlain by at least 37 flood beds. An estimated flood recurrence interval of

25 years indicates that these 37 floods span ~900 years. This age helps constrain the timing of glacial Lake Missoula flooding during marine oxygen isotope stage 2 and is consistent with other published ages on the advance and retreat of the Okanogan, Columbia River, and Purcell Trench lobes of the Cordilleran ice sheet.

## Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada through Discovery Grant (24595) to Clague and an NSERC PGS B Scholarship to Hanson. Access to some of the field sites was granted by the Confederated Tribes of the Colville Reservation. J. Koch, T. Lakeman, and C. Reiss assisted with the field work. R. Waitt offered helpful suggestions for improving the manuscript.

## References

Ashley, G.M., 1975. Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts-Connecticut. In: Jopling, A.V., McDonald, B.V. (Eds.), Glaciofluvial and Glaciolacustrine Sedimentation, Soc. Econ. Paleontol. Mineral. Special Pap. 23, pp. 304–320.
Ashley, G.M., 2002. Glaciolacustrine environments. In: Menzies, J. (Ed.), Modern and Past Glacial Environments. Butterworth-Heinemann Publications, Oxford, pp. 335–362.
Atwater, B.F., 1983. Guidebook for 1983 Friends of the Pleistocene field trip to the Sanpoil River Valley, northeastern Washington. U.S. Geol. Surv. Open File Rep. 83–456.
Atwater, B.F., 1984. Periodic floods from glacial Lake Missoula into the Sanpoil Arm of glacial Lake Columbia, northeastern Washington. Geology 12, 464–467.
Atwater, B.F., 1986. Pleistocene glacial lake deposits of the Sanpoil River Valley, northeastern Washington. U.S. Geol. Surv. Bull. 1661.
Atwater, B.F., 1987. Status of glacial Lake Columbia during the last floods from glacial Lake Missoula. Quat. Res. 27, 182–201.
Baker, V.R., 1973. Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. Geol. Soc. Am. Spec. Pap. 144.
Benn, D.I., 1996. Subglacial and subaqueous processes near a glacier grounding line: sedimentological evidence from a former ice-dammed lake, Achnasheen Scotland. Boreas 35, 23–36.
Best, J.L., Kostaschuk, R.A., Peakall, J., Villard, P.V., Franklin, M., 2005. Whole flow field dynamics and velocity pulsing within natural sediment-laden underflows. Geology 33, 765–768.
Bjornstad, B.N., 1980. Sedimentology and Depositional Environment of the Touchet Beds, Walla Walla River Basin, Washington (M.Sc. thesis). Eastern Washington University, Cheney, WA.
Bretz, J.H., 1923. Glacial drainage on the Columbia Plateau. Geol. Soc. Am. Bull. 34, 573–608.
Bretz, J.H., 1928. Bars of Channeled Scabland. Geol. Soc. Am. Bull. 39, 643–701.
Bretz, J.H., 1932. The Channeled Scabland. In: International Geological Congress Guidebook 22: Excursion C-2.
Bretz, J.H., Smith, H.T.U., Neff, G.E., 1956. Channeled Scabland of Washington: new data and interpretations. Geol. Soc. Am. Bull. 67, 957–1049.
Bunker, R.C., 1982. Evidence of multiple late-Wisconsin floods from glacial Lake Missoula in Badger Coulee. Wash. Quat. Res. 18, 17–31.
Carling, P.A., 2013. Freshwater megaflood sedimentation: what can we learn about generic processes? Earth Sci. Rev. 125, 87–113.
Cheel, R.J., Rust, B.R., 1982. Coarse grained facies of glacio-marine deposits near Ottowa [sic], Canada. In: Davidson-Arnott, R., Nickling, W., Fahey, B.D. (Eds.), Research in Glacial, Glacio-fluvial, and Glacio-lacustrine Systems. Proceedings – Guelph Symposium on Geomorphology. University of Guelph, Guelph, ON, pp. 279–295.
Clague, J.J., Armstrong, J.E., Mathews, W.H., 1980. Advance of the late Wisconsinan Cordilleran ice sheet in southern British Columbia since 22,000 yr BP. Quat. Res. 13, 322–326.
Clague, J.J., Barendregt, R., Enkin, R.J., Foit Jr., F.F., 2003. Paleomagnetic and tephra evidence for tens of Missoula floods in southern Washington. Geology 31, 247–250.
Clarke, G.K.C., Mathews, W.H., Pack, R.T., 1984. Outburst floods from glacial Lake Missoula. Quat. Res. 22, 289–299.
Craig, R.G., 1987. Dynamics of a Missoula flood. In: Mayer, L., Nash, D. (Eds.), Catastrophic Flooding. Allen and Unwin, London, pp. 305–332.
Denlinger, R.P., O'Connell, D.R.H., 2010. Simulations of cataclysmic outburst floods from Pleistocene glacial Lake Missoula. Geol. Soc. Am. Bull. 122, 678–689.
Eyles, N., Clague, J.J., 1991. Glaciolacustrine sedimentation during advance and retreat of the Cordilleran ice sheet in central British Columbia. Géogr. phys. Quat. 45, 317–331.
Eyles, N., McCabe, A.M., 1989. The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. Quat. Sci. Rev. 8, 307–351.
Eyles, N., Eyles, C.H., Miall, A.D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. Sedimentology 30, 393–410.
Flint, R.F., 1935. Glacial features of the southern Okanogan region. Geol. Soc. Am. Bull. 46, 169–194.
Flint, R.F., 1936. Stratified drift and deglaciation of eastern Washington. Geol. Soc. Am. Bull. 47, 1849–1884.
Flint, R.F., 1937. Pleistocene drift border in eastern Washington. Geol. Soc. Am. Bull. 48, 203–232.
Flint, R.F., Irwin, W.H., 1939. Glacial geology of Grand Coulee dam, Washington. Geol. Soc. Am. Bull. 50, 661–680.
Gaylord, D.R., Pope, M.C., Cabbage, P.R., Glover III, J.F., Anfinson, O.A., Baar, E.E., Vervoort, J.D., 2007. Provenance of glacial outburst flood deposits in the Channeled Scabland, WA; influence of glacial Lake Missoula, meltwater, Snake River, and Bonneville flood sources. Geol. Soc. Am. Abstr. Progr. 39, 82.
Hanson, M.A., 2013. Sedimentological and Paleomagnetic Study of Glacial Lake Missoula Lacustrine and Flood Sediment (Ph.D thesis). Simon Fraser University, Burnaby, BC.
Hanson, M.A., Enkin, R.J., Barendregt, R.W., Clague, J.J., 2015. Provenance and deposition of glacial Lake Missoula lacustrine and flood sediments from rock magnetic properties. Quat. Res. 83, 166–177.
Jones, F.O., Embody, D.R., Peterson, W.L., 1961. Landslides along the Columbia River Valley, northeastern Washington. U.S. Geol. Surv. Prof. Pap. 367.
Kovanen, D.J., Slaymaker, O., 2004. Glacial imprints of the Okanogan Lobe, southern margin of the Cordilleran ice sheet. J. Quat. Sci. 19, 547–565.
Kuehn, S.C., Froese, D.G., Carrara, P.E., Foit Jr., F.F., Pearce, N.J.G., Rotheisler, P., 2009. Major- and trace-element characterization, expanded distribution, and a new chronology for the latest Pleistocene Glacier Peak tephras in western North America. Quat. Res. 71, 201–216.
Levish, D.R., 1997. Late Pleistocene Sedimentation in Glacial Lake Missoula and Revised Glacial History of the Flathead Lobe of the Cordilleran Ice Sheet, Mission Valley, Montana (Ph.D. thesis). University of Colorado, Boulder, CO.
MacEachern, J.A., Roberts, M.C., 2013. Ichnological evidence of jökulhlaup deposit recolonization from the Touchet Beds, Mabton, WA, USA. Quat. Res. 79, 37–48.
Maizels, J., 1989. Sedimentology, paleoflow dynamics and flood history of jökulhlaup deposits: paleohydrology of Holocene sediment sequences in southern Iceland sandur deposits. J. Sediment Petrol. 59, 204–223.
Maizels, J., 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. Sediment. Geol. 85, 299–325.
Maizels, J., 1997. Jökulhlaup deposits in proglacial areas. Quat. Sci. Rev. 16, 793–819.
Miall, A.D., 1977. A review of the braided river depositional environment. Earth Sci. Rev. 13, 1–62.
Miall, A.D., 1978. Lithofacies types and vertical profile models in braided rivers. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Can. Soc. Petrol. Geol., Calgary, AB, pp. 597–604.
Mulder, T., Syvitski, J.P.M., Migeon, S., Faugères, J.-C., Savoye, B., 2003. Marine hyperpycnal flows: Initiation, behavior and related deposits: a review. Mar. Petrol. Geol. 20, 861–882.
Mulder, T., Zaragosi, S., Jouanneau, J.-M., Bellaiche, G., Guérinaud, S., Querneau, J., 2009. Deposits related to the failure of the Malpasset Dam in 1959: an analogue for hyperpycnal deposits from jökulhlaups. Mar. Geol. 260, 81–89.
O'Connor, J.E., 1993. Hydrology, hydraulics, and geomorphology of the Bonneville flood. Geol. Soc. Am. Spec. Pap. 274.
O'Connor, J.E., Baker, V.R., 1992. Magnitudes and implications of peak discharges from glacial Lake Missoula. Geol. Soc. Am. Bull. 104, 267–279.
Pardee, J.T., 1910. The glacial Lake Missoula, Montana. J. Geol. 18, 376–386.
Pardee, J.T., 1918. Geology and mineral deposits of the Colville Indian Reservation, Washington. U.S. Geol. Surv. Bull. 1–186.
Pardee, J.T., 1942. Unusual currents in glacial Lake Missoula, Montana. Geol. Soc. Am. Bull. 53, 1570–1599.
Paterson, J.T., Cheel, R.J., 1997. The depositional history of the Bloomington Complex, an ice-contact deposit in the Oak Ridges Moraine, southern Ontario, Canada. Quat. Sci. Rev. 16, 705–719.
Peters, E.K., 2003. Evidence for two outburst floods of non-Missoula origin in NE Washington state. Geol. Soc. Am. Abstr. Progr. 35, 217.
Peters, E.K., Gaylord, D.R., Pope, M., 2002. Large-scale foreset, boulder-gravel beds in the lower Spokane River valley, northeastern Washington. Geol. Soc. Am. Abstr. Progr. 34, 109.
Porter, S.C., 1978. Glacier Peak tephra in the North Cascade Range, Washington: stratigraphy, distribution, and relationship to Late-glacial events. Quat. Res. 10, 30–41.
Richmond, G.M., Fryxell, R., Neff, G.E., Weis, P.L., 1965. The Cordilleran ice sheet of the northern Rocky Mountains, and related Quaternary history of the Columbia Plateau. In: Wright Jr., H.E., Frey, D.G. (Eds.), The Quaternary of the United States. Princeton University Press, Princeton, NJ, pp. 231–242.
Rushmer, E.L., 2006. Sedimentological and geomorphological impacts of the jökulhlaup (glacial outburst flood) in January 2002 at Kverkfjöll, northern Iceland. Geogr. Ann. A 88, 43–53.
Russell, A.J., 2007. Controls on the sedimentology of an ice-contact jökulhlaups-dominated delta, Kangerlussuaq, west Greenland. Sediment. Geol. 193, 131–148.
Russell, A.J., Knudsen, Ó., 1999. An ice-contact rhythmite (turbidite) succession deposited during the November 1996 catastrophic outburst flood (jökulhlaup), Skeidarárjökull. Icel. Sediment. Geol. 127, 1–10.
Rust, B.R., Romanelli, R., 1975. Late Quaternary subaqueous outwash deposits near

Ottawa, Canada. In: Jopling, A.V., McDonald, B.V. (Eds.), Glaciofluvial and Glaciolacustrine Sedimentation. Soc. Econ. Paleontol. Mineral. Spec. Pap. 23, pp. 177–192.
Shaw, J., Munro-Stasiuk, M., Sawyer, B., Beaney, C., Lesemann, J.-E., Musacchio, A., Rains, B., Young, R.R., 1999. The channeled Scabland: back to Bretz? Geology 27, 605–608.
Smith, L.N., 2006. Stratigraphic evidence for multiple drainings of glacial Lake Missoula along the Clark Fork River, Montana, USA. Quat. Res. 66, 311–322.
Smith, N.D., Ashley, G., 1985. Proglacial lacustrine environment. In: Ashley, G.M., Shaw, J., Smith, N.D. (Eds.), Glacial Sedimentary Environments, Soc. Econ. Paleont. Mineral. Short Course 16, pp. 135–216.
Waitt, R.B., 1980. About forty last-glacial Lake Missoula jökulhlaups through southern Washington. J. Geol. 88, 653–679.
Waitt, R.B., 1984. Periodic jökulhlaups from Pleistocene glacial Lake Missoula – new evidence from varved sediment in northern Idaho and Washington. Quat. Res. 22, 46–58.
Waitt, R.B., 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula. Geol. Soc. Am. Bull. 96, 1271–1286.
Waitt, R.B., Thorson, R.M., 1983. The Cordilleran Ice Sheet in Washington, Idaho, and Montana. In: Wright Jr., H.E. (Ed.), Late-Quaternary Environments of the United States, Volume 1: the Late PleistoceneUniversity of Minnesota Press, Minneapolis, MN, pp. 53–70.
Waitt, R.B., Denlinger, R.P., O'Connor, J.E., 2009. Many monstrous Missoula floods down Channeled Scabland and Columbia Valley. In: O'Connor, J., Madin, I. (Eds.), Volcanoes to Vinyards: Geological Field Trips through the Dynamic Landscape of the Pacific Northwest, GeolSoc. Am. Field Guides 15, pp. 737–774. http://dx.doi.org/10.1130/2009.fld019(32).
Zuffa, G.G., Normark, W.R., Serra, F., Brunner, C.A., 2000. Turbidite megabeds in an oceanic rift valley recording jökulhlaups of late Pleistocene glacial floods of the western United States. J. Geol. 108, 253–274.