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Periodic Jökulhlaups from Pleistocene Glacial Lake Missoula—New Evidence from Varved Sediment in Northern Idaho and Washington

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Newly examined exposures in northern Idaho and Washington show that catastrophic floods from glacial Lake Missoula during late Wisconsin time were repeated, brief jökulhlaups separated by decades of quiet glaciolacustrine and subaerial conditions. Glacial Priest Lake, dammed in the Priest River valley by a tongue of the Purcell Trench lobe of the Cordilleran ice sheet, generally accumulated varved mud; the varved mud is sharply interrupted by 14 sand beds deposited by upvalley-running currents. The sand beds are texturally and structurally similar to slackwater sediment in valleys in southern Washington that were backflooded by outbursts from glacial Lake Missoula. Beds of varved mud also accumulated in glacial Lake Spokane (or Columbia?) in Latah Creek valley and elsewhere in northeastern Washington; the mud beds were disrupted, in places violently, during emplacement of each of 16 or more thick flood-gravel beds. This history corroborates evidence from southern Washington that only one graded bed is deposited per flood, refuting a conventional idea that many beds accumulated per flood. The total number of such floodlaid beds in stratigraphic succession near Spokane is at least 28. The mud beds between most of the floodlaid beds in these valleys each consist of between 20 and 55 silt-to-clay varves. Lacustrine environments in northern Idaho and Washington therefore persisted for two to six decades between regularly recurring, colossal floods from glacial Lake Missoula.

INTRODUCTION

During late Wisconsin time, the Cordilleran ice sheet advanced into Washington and Idaho and dammed several glacial lakes in the Columbia drainage basin (Fig. 1). At the glacial maximum the Purcell Trench lobe dammed glacial Lake Missoula (maximum altitude 1300 m), whose maximum volume of 2130 km^3 was about that of present Lake Ontario. Glacial Lake Missoula discharged as enormous floods beneath and through the great dam of ice formed by the Purcell Trench lobe and from there coursed mainly southwest down the wide Rathdrum valley and across the Channeled Scabland, as well as down the Columbia River valley (Fig. 1) (Bretz *et al.*, 1956; Bretz, 1969; Baker, 1973; Waitt, 1980).

Analysis of about 40 superposed, thick graded rhythmites in backflooded tributaries of the lower Columbia River led me to infer that each rhythmite represents a separate, enormous Missoula flood and that decades of subaerial conditions prevailed between the sudden accumulation of each rhythmite (Waitt, 1980). This hypothesis that glacial Lake Missoula discharged regularly and repeatedly as huge jökulhlaups (Waitt, 1979, 1980, 1982) has not been generally accepted (Patton *et al.*, 1979; Bjornstad, 1980, 1982; Baker, 1981, pp. 252–253; Bunker, 1982). Without refuting evidence offered for the dozens-of-floods hypothesis, others have maintained that the rhythmic bedding could have resulted from transient hydraulic surging during one or a few floods. The sparse field evidence offered in support of the conventional one-flood or few-flood hypothesis is ambiguous, but it is also true that I demonstrated unassailable evidence of a lengthy pause between only some of the roughly 40 floodlaid beds in southern Washington. The dozens-of-floods hypothesis is partly based on the fact that each of the superposed graded beds closely repeats a particular sedimentary motif. I contend that each bed formed by repetition of one set of catastrophic-fluvial processes, not some beds by one process, other identical beds by entirely different processes (Waitt, 1980). The unambiguous evidence that certain rhythmites are each the result of a separate flood suggests that each of the other identical beds is also a product of a separate flood.

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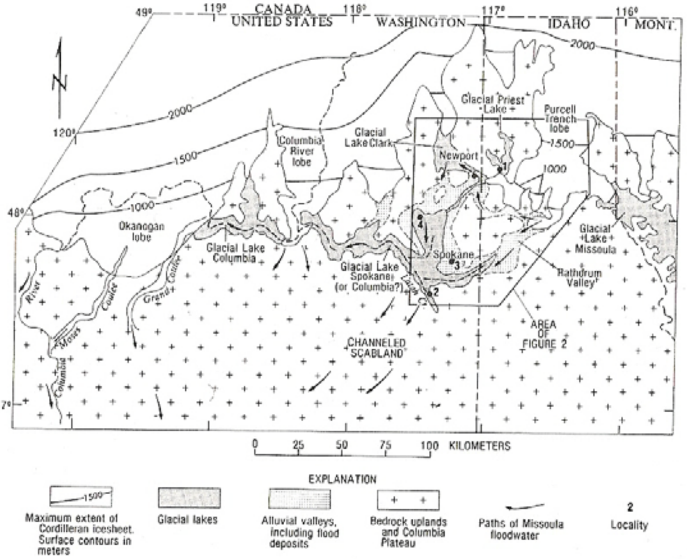

FIG. 1. Map showing revised limits of the Cordilleran ice sheet and of Missoula floods; ice-sheet contours in meters (redrawn from Waitt and Thorson, 1983, Fig. 3–1).

New evidence from northern Idaho and Washington now confirms and reaffirms the one-bed-per-flood hypothesis (Fig. 2). Varved, clayey lacustrine sequences are regularly and repeatedly interrupted by beds of much coarser material deposited by catastrophic backflooding from conduits of the great Missoula floods (Waitt, 1982, 1983a, b; Waitt and Thorson, 1983; Atwater, 1983). That varved lacustrine beds separate each of many beds of coarse backflood sediment shows unambiguously that recurring catastrophic jökulhlaups from glacial Lake Missoula were separated from each other by decades.

Figure 3 illustrates perceived relations between rhythmically bedded deposits in southern Washington, in northern Washington, and in the Lake Missoula basin. These scattered rhythmite deposits are inferred to be cognate to the great Missoula floods, because they can be accounted for by no other process; their inferred correlation is compatible with all known time-stratigraphic information (e.g., Waitt, 1980, 1985; Waitt and Thorson, 1983). The periods of flooding are best recorded in backflooded valleys scattered between Idaho and northwestern Oregon, but the interflood intervals are most convincingly demonstrated in the deposits of contemporaneous glacial lakes in northern Washington, Idaho, and Montana. Details of graded flood rhythmites in southern Washington and of rhythmites from glacial Lake Mis-

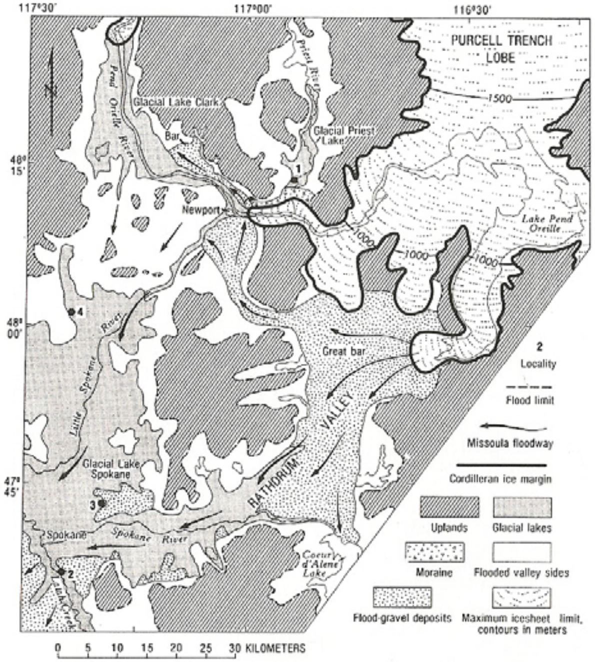

FIG. 2. Map of Pend Oreille, Priest River, and Spokane areas, showing paths of Missoula floodwater. The lake depicted in the Spokane area is the maximum "Lake Spokane" that the Columbia River lobe could have dammed; Lake Columbia I, dammed by the Okanogan lobe, was more extensive (Waitt and Thorson, 1983, Fig. 3–1). The areas of these lakes are dominated by Missoula-flood deposits.

soula are given by Waitt (1980); regional relations are elaborated elsewhere (Waitt, 1980, 1985; Waitt and Thorson, 1983; R. B. Waitt, E. P. Kiver, and D. F. Stradling, unpublished report).

NEW EVIDENCE

Purcell Trench Lobe and Priest River Valley

A western distributary of the Purcell Trench lobe built a moraine astride the lower end of the Priest River valley, thus damming glacial Priest Lake (altitude 690 m) (Waitt and Thorson, 1983). Till of the moraine grades abruptly upvalley into sandy gravel, gravelly sand, sand, and layered mud.[1] Other ice lobes dammed glacial Lakes Columbia, Spokane, and Clark in the Columbia, Spokane, and Pend Oreille valleys (Fig. 1) (Waitt and Thorson, 1983). A newly recognized huge bar of stratified gravel and several other deposits in the Pend Oreille River valley west of the Priest River confluence reveal that the Missoula floods not only discharged down the principal Rathdrum valley conduit, but also flowed northwestward and into the Pend Oreille River valley west of the ice margin at Newport (Fig. 2) (Waitt and Thorson, 1983).

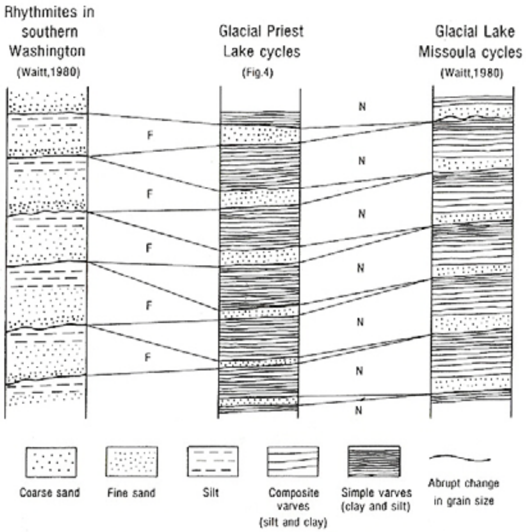

FIG. 3. Inferred relation of rhythmic beds in southern Washington, glacial lakes in northern Idaho and Washington, and glacial Lake Missoula in Montana. Tie lines represent time horizons. F, floodlaid bed; N, nonflood lacustrine bed.

Glacial Priest Lake is manifested in the lower Priest River valley by beds of varved silt and clay. A 20-m section 1.5 km upvalley of the moraine (Figs. 1, 2, loc. 1) shows beds of varved silt and clay sharply punctuated by beds of fine sand spaced at fairly regular intervals of 50–100 cm (Fig. 4). Above and below each sand bed, the mud beds consist mostly of 20 to 50 varves but also partly of nonvarved silt and clay. Each varve, 1–4 cm thick, is a laterally continuous couplet of silt (summer layer) grading abruptly upward to clay (winter layer) (Fig. 5). Although the contact between a silt and overlying clay lamina is commonly fairly sharp, the contact between the clay and overlying silt lamina is much sharper. Clay laminae persist through the entire mud section, forming one-fifth to four-fifths of each varve. The regular, laterally persistent couplets are similar or identical to classic varves that formed in other Pleistocene and Holocene glacial lakes (Antevs, 1922, 1951; Ashley, 1975; Gustavson, 1975). Walker (1967, pp. 84–85) described and analyzed the Priest valley section; I reaffirm his inference that the regular silt-to-clay couplets are annual varves. Because glacial Priest Lake was near the ice-sheet margin, the varve couplets tend to be much thicker and coarser than varves that contemporaneously accumulated in arms of glacial lakes much farther from the ice margin (see below).

The varved mud beds are sharply punctuated by 14 laterally persistent find-sand beds that are four to five grain-size (ϕ) intervals coarser than the mud beds (Figs. 4, 6). The sand beds have somewhat variable

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[1] Grain-size designations refer to median size, determined in the field by hand-lens comparison to Wentworth size standards. Median sizes finer than about 6 ϕ (medium silt) are judged partly by plasticity and grittiness. Nomenclature is approximately that of Folk (1974, p. 28).

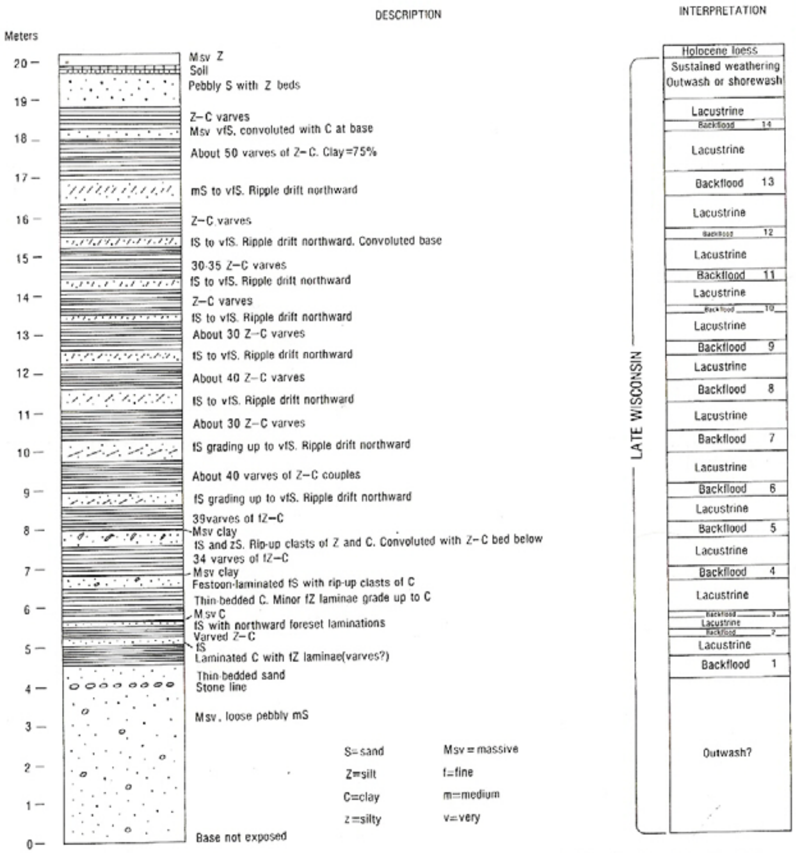

FIG. 4. Stratigraphic section of interbedded lacustrine and catastrophic-flood sediment in the Priest River valley along Peninsula Road in SW1/4 SE1/4 sec. 1, T. 56 N., R. 5 W. (USGS Priest River 7.5-min quadrangle).

sedimentary structures, but ripple-drift laminae near the base or middle of most beds dip and climb universally upvalley, indicating *up*valley-directed paleocurrents (Fig. 6). Each thick sand bed shows an upward sequence of sedimentary structures similar though not identical to the sequence within a typical graded rhythmite in the backflooded valleys of southern Washington (compare with Waitt, 1980, Figs. 3, 5, and p. 656). The most complete sequence of structures within a Priest valley sand bed is: a basal 2–5 cm of reversely graded and plane-laminated coarse silt to very fine sand; overlain by 20–80 cm of normally graded fine sand showing several tiers of "Type A" ripple-drift laminae with upvalley-dipping foresets; overlain by 5–10 cm of "draped" to plane-laminated to massive very fine sand (Fig. 6). Such a sequence simulated in flumes accumulates within hours (Ashley *et al.*, 1982).

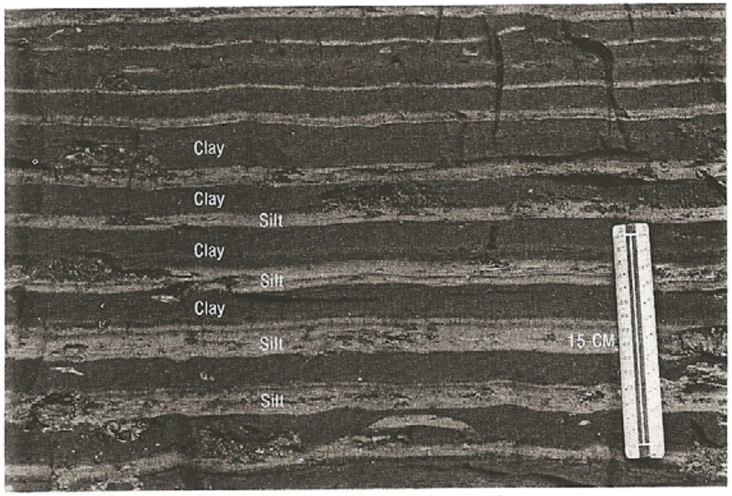

FIG. 5. Detail of varves at Priest valley section. Silty clay is dark; sandy silt is light.

The base of each sand bed overlies clayey varves sharply (Figs. 4, 6); the bases of some sand beds are intricately convoluted with the underlying clayey mud, and some sand beds contain many angular rip-up clasts of the clay. The reverse-graded base of some floodlaid beds consists of imported sand, and suggests that the flood achieved its maximum velocity gradually, as do modern jökulhlaups (Mathews, 1973; Björnsson, 1974).

The top of each sand bed is sharp or grades over 2–5 cm into an overlying bed of massive silty clay; some sand beds are capped by 3–5 cm of massive silt topped by 3–5 cm of massive clay (Figs. 4, 6). I attribute the massive, graded silt and clay bed atop some floodlaid beds to gradual settling over several days or months of fine particles that the invading flood imported or stirred up from the lake bottom. I agree with Atwater's (1983) analysis of similar beds in the Sanpoil valley that the massive layer is genetically part of the top of the floodlaid bed, not part of the overlying interflood glaciolacustrine bed.

This section reveals that glacial Priest Lake was generally a quiet lacustrine environment in which regular varves accumulated year by year. This environment was sharply interrupted every 20 to 50 years or so by an energetic upvalley-directed current that swiftly deposited a bed of fine sand, after which the turbid lake water cleared after days or weeks. Walker (1967) correctly recognized that the alternating sand and mud beds of the Priest valley section reveal an alternation between glaciolacustrine and flood environments. But he inferred (1) that the varved sediment accumulated in an arm of glacial Lake Clark, which was dammed by a separate lobe of ice to the west (Fig. 1, 2), and (2) that the interruptions in lacustrine sedimentation revealed rapid escape of Lake Clark water from the Priest River valley. This argument is partly refuted and partly modified: (1) the well-defined upper limit of silt deposits of glacial Lake Clark (altitude 650 m) is graded to a lake spillway 20 to 40

FIG. 6. Detail of graded sand bed within the Priest valley section. View is southeast: ripple-drift foreset laminae are directed upvalley, to left.

m below the Priest River section, and glacial Priest Lake was therefore separate from glacial Lake Clark (Fig. 2); and (2) the upvalley-directed paleocurrents show that the strong currents backflooded *into* the Priest River valley from the Pend Oreille valley, not vice versa. The only source of water of sufficient volume and altitude (Waitt, 1980, Table 3; Waitt and Thorson, 1983) to backflood the Priest valley was outbursts from glacial Lake Missoula, from whose outlet near modern Lake Pend Oreille a valley system led around the ice margin to the Priest River valley (Figs. 1, 2).

Whereas the most complete sections of lacustrine rhythmites in the Lake Missoula basin and of flood rhythmites in southern Washington and western Oregon testify to some 40 major floods (Waitt, 1980), the Priest valley section reveals only 14 such events. But as long as the ice lobe lay astride the valley mouth (Fig. 2), outwash dominated the area of the Priest valley section. Only after the ice retreated and the valley was dammed by the moraine alone was the supply of coarse sediment into glacial Priest Lake reduced enough that silt and clay could accumulate as discrete beds.

Latah Creek Valley

As long as the Okanogan lobe of Cordilleran ice blocked the upper end of the Grand Coulee (Fig. 1), glacial Lake Columbia I was dammed to altitude 730 m—a lake as deep as 600 m that backed up in the Spokane River valley (Waitt and Thorson, 1983). The Columbia River lobe of Cordilleran ice independently dammed a shallower glacial Lake Spokane (Fig. 1) (Waitt and Thorson, 1983); the relative effects of the two glacial lakes in the Spokane valley are undeciphered. The upper Spokane valley, a wide, steep-walled trough commonly called "Rathdrum Prairie" but herein "Rathdrum valley," was the main conduit of Lake Missoula floodwater into Washington (Bretz *et al.*, 1956; Baker, 1973).

In lower Latah Creek valley (Figs. 1, 2, loc. 2), a Spokane River tributary south of Spokane, 16 thick graded beds of gravel and sand with south-dipping (upvalley-directed) foreset beds are each topped by a thin bed of plane-laminated mud. The mud beds, 0 to 20 cm thick, each consist of as many as 55 regular, clayey varves (Fig. 7). This arm of glacial Lake Columbia or Spokane was much farther from the ice margin than was lower Priest Lake: the couplets at Latah Creek are alternations of gray silty clay and brown fine clay, although the bases of a few varves include minor silt or very fine sand. The varves average only 2.5 mm in thickness (Fig. 8)—much thinner as well as finer than the Priest valley varves. The dominating sand-and-gravel beds 1 to 4 m thick are some 8 to 12 grain-size (ϕ) units coarser than the clay beds that they regularly interrupt (Fig. 9). Scattered through the gravel beds are boulders as large as 90 cm in intermediate diameter of locally derived basalt, sandstone, and siltstone. Latah Creek valley is carved in basalt, but the sand-and-gravel beds with upvalley-dipping foreset beds consist partly of angular to rounded exotic clasts of diverse nonbasaltic crystalline-rock types

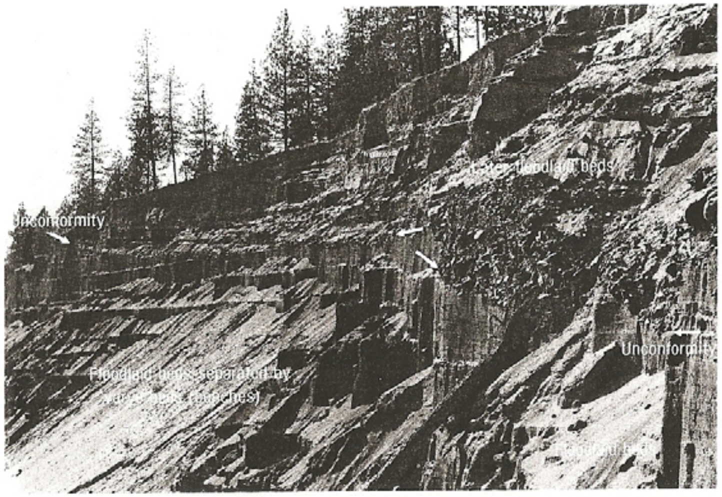

FIG. 7. Floodlaid beds along northeast side of Latah Creek in SW1/4 SE1/4 sec. 31, T, 25 N., R. 43 E. (U.S. Geological Survey Spokane SW 7.5-min quadrangle). Below gravel-lined disconformity (arrows), top of each bench is varved silt and clay, which separate thick beds of sand and gravel having upvalley-directed forset beds. Above disconformity are about 12 more-lenticular beds of gravel topped by graded sand and silt also having foresets and ripple-drift that dip upvalley: they are deposits of Missoula floods that arrived after the glacial lake in the valley had lowered or drained.

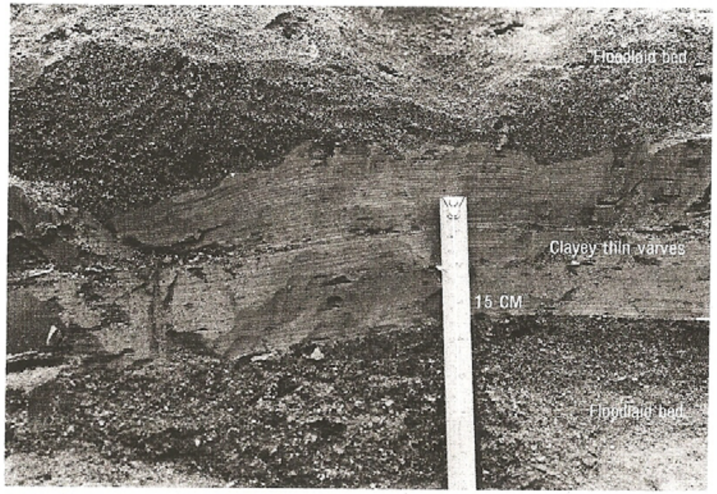

FIG. 8. Clay bed comprising 51 thin clay varves between coarse floodlaid beds low in Latah Creek section. Overlying floodlaid bed eroded and segmented the bed of clay.

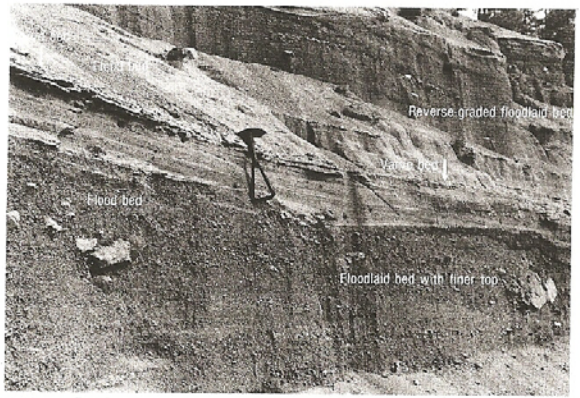

FIG. 9. Two coarse flood-gravel beds separated by varved-clay bed at Latah Creek section. Base of upper gravel bed is reversely graded. Shovel handle = 43 cm.

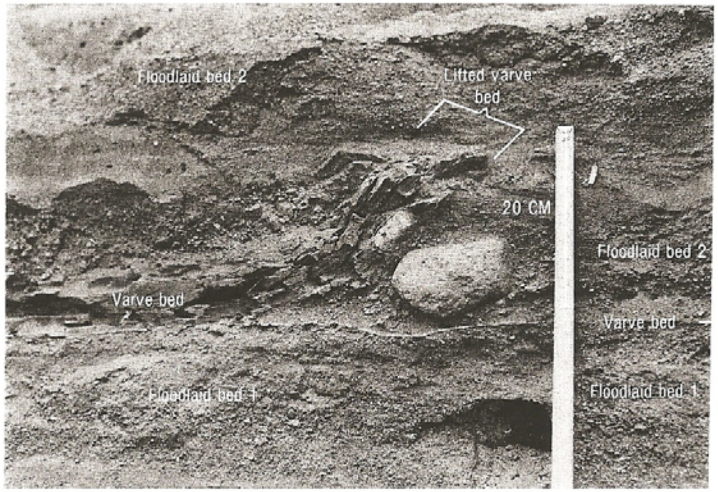

FIG. 10. Violently invasive flood bed dividing a varved-clay bed at Latah Creek section. Cobble-bearing part of flood bed was injected beneath and lifted the varve bed; the dismembered varve bed is a source of rip-up clasts to the upper part of floodlaid bed.

like those of the gravel flooring the Rathdrum valley floodway.

The gravel–sand beds apparently are bedload material carried by floods down Rathdrum valley that were deep enough to sweep violently up Latah Creek valley. Each graded bed is eroded into the underlying clay bed, which is variously convoluted or injected by the coarse floodlaid bed (Fig. 10). Some varve beds overlie a poorly sorted bed rich in rip-up clasts that was injected as a sill from the overlying floodlaid bed (Fig. 11). The large boulders, the injected beds, and disruption of clay beds show that the gravel beds were violently floodlaid: they are not outwash deltas, especially not in this area tens of kilometers beyond the well-defined late Wisconsin ice limits (Figs. 1, 2) (Waitt and Thorson, 1983). The unweathered, uncemented state of the gravel and the absence of weathering and soil horizons within these beds indicate a late Wisconsin age, not the penultimate-glacial age that Richmond *et al.* (1965) and some earlier workers assigned to deposits near Spokane.

The Latah Creek section shows that the usual sedimentation in late Wisconsin glacial Lake Columbia or Spokane was quiet and distant from sediment sources, but that it was suddenly interrupted at least 16 times by the violent influx of coarse flood sediment. After each such catastrophic interlude, quiet glaciolacustrine sedimentation resumed for at least several years, generally for decades.

The succession of thick varve-capped flood beds is truncated by a disconformity, which is overlain by a succession of about 12 thinner graded beds that also have upvalley-dipping foreset structures. These upper beds appear less rhythmic partly because they are not each capped by a varve bed (Fig. 7). I infer these beds to be deposits of 12 or more Missoula floods that swept up the valley after the glacial lake in the valley had lowered or drained and was thus no longer producing varves at this altitude in between floods. The total number of separate floods represented by the Latah Creek section is thus at least 28, of which 16 below the disconformity are topped by varved-clay beds.[2]

[2] The Latah Creek section has been independently studied by Rigby (1982), with some of whose conclusions I disagree. I respond to criticism and alternate hypotheses in Waitt (1985).

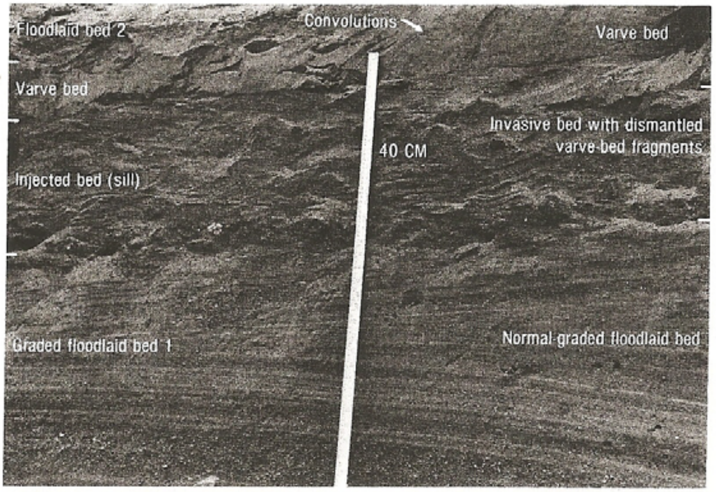

FIG. 11. Flood-injected invasive bed beneath varved-clay bed at Latah Creek section.

Spokane Drainage Basin North of Spokane

Parts of the valleys and uplands of the Spokane drainage basin north of Spokane are discontinuously veneered by gravel and sand whose foreset beds dip west, southwest, or south. Such deposits reveal that high-velocity discharges along the upper Spokane and Little Spokane valleys were deep enough to fill valleys and cross adjacent divides. Some of these deposits contain huge boulders or are associated with giant current dunes or huge barlike forms, all further indicating their emplacement by extreme discharges of water (Kiver and Stradling, 1982; Waitt, Kiver, and Stradling, unpublished report). At most sites the gravel beds overlie each other with no intervening fine sediment. But at some sites (Fig. 2, locs. 3, 4) as many as four beds of flood gravel or sand are each separated by intervening clay–silt beds centimeters thick (Fig. 12), some comprising as many as 35 varves. Each bed of varved clay and silt indicates that decades of quiet sedimentation in glacial Lake Columbia or Spokane elapsed between each separate catastrophic flood.

DISCUSSION

Several independent lines of field evidence in Montana, southern Washington, and northern Oregon indicate that the great Missoula floods of late Wisconsin time were at least 40 in number and were regularly repeating (Waitt, 1980)—a hypothesis disputed by some authors. In northern Idaho and Washington, sediment between flood-deposited beds includes laminated beds of fine silt to clay centimeters thick. For clay particles to settle through unagitated, deep, fresh water and accumulate centimeters thick requires weeks or months. Fine silt and clay beds decimeters thick comprise as many as 55 varves, which all together add up to many hundreds of couplets. Here is firm evidence that in the glacial lakes of northern Idaho and Washington still-water sediment accumulated for centuries, maybe millennia. This long-term, quiet glaciolacustrine sedimentation was interrupted periodically—once every few decades—by an abrupt accumulation of sand or gravel deposited by swift-moving water that was deep and voluminous enough to overtop valley divides and backflood up capacious valleys.

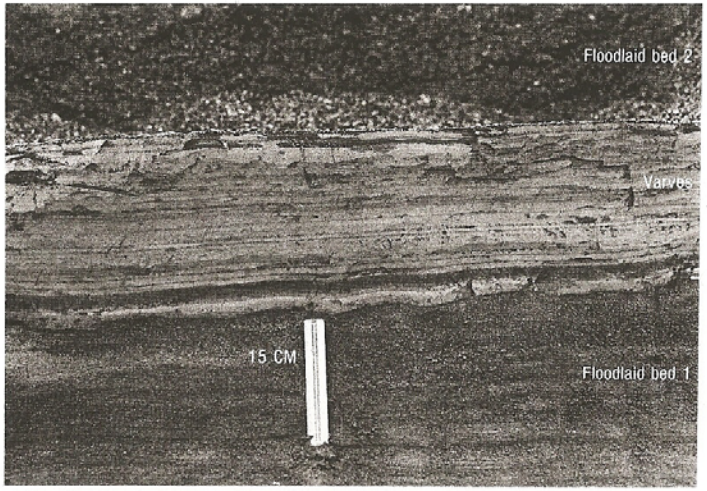

FIG. 12. Varved clay-silt bed separating floodlaid gravel beds in gravel pit at locality 4.

The Priest River section, whose several beds of varved silt and clay are each 50 to 100 cm thick and consist mainly of 20 to 50 varves, is compelling evidence that the long-term environment there in late Fraser time was glaciolacustrine. The analogous but finer and thinner varves at Latah Creek number as many as 55 between the floodlaid beds. Two to six decades thus separated each swift, energetic backflood up these valleys. The coarse flood beds in Latah Creek valley and their dismemberment of the varved-clay beds show that the backfloods were violent, not merely outwash deltas building into the lake.

The straightforward interpretation for the origin of these and other sections in northern Idaho and Washington (Waitt, 1982, 1983a, b; Atwater, 1983) is similar to that inferred from different evidence in the backflooded valleys of southern Washington (Waitt, 1980). The only source with enough altitude and volume to backflood the Priest River and Latah valleys catastrophically and to inundate other nearby areas tens to hundreds of meters deep was the same colossal floods from glacial Lake Missoula that deluged the vast region of the Channeled Scabland and Columbia River valley to the south and west. Glacial Lake Missoula must have drained as a catastrophic jökulhlaup once every few decades. A forthcoming report (Waitt, 1985) explains how the lake drained subglacially each time the gradually filling lake rose to a critical level that made the ice dam hydrostatically buoyant.

ACKNOWLEDGMENTS

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