Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula

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ABSTRACT

Two classes of field evidence firmly establish that late Wisconsin glacial Lake Missoula drained periodically as scores of colossal jökulhlaups (glacier-outburst floods). (1) More than 40 successive, flood-laid, sand-to-silt graded rhythmites accumulated in backflooded valleys in southern Washington. Hiatuses are indicated between flood-laid rhythmites by loess and volcanic ash beds. Disconformities and nonflood sediment between rhythmites are generally scant because precipitation was modest, slopes gentle, and time between floods short. (2) In several newly analyzed deposits of Pleistocene glacial lakes in northern Idaho and Washington, lake beds comprising 20 to 55 varves (average = 30–40) overlie each successive bed of Missoula-flood sediment. These and many other lines of evidence are hostile to the notion that any two successive major rhythmites were deposited by one flood; they dispel the notion that the prodigious floods numbered only a few.

The only outlet of the 2,500-km^3 glacial Lake Missoula was through its great ice dam, and so the dam became incipiently buoyant before the lake could rise enough to spill over or around it. Like Grímsvötn, Iceland, Lake Missoula remained sealed as long as any segment of the glacial dam remained grounded; when the lake rose to a critical level ~600 m in depth, the glacier bed at the seal became buoyant, initiating underflow from the lake. Subglacial tunnels then grew exponentially, leading to catastrophic discharge. Calculations of the water budget for the lake basin (including input from the Cordilleran ice sheet) suggest that the lakes filled every three to seven decades. The hydrostatic prerequisites for a jökulhlaup were thus re-established scores of times during the 2,000- to 2,500-yr episode of last-glacial damming.

J Harlen Bretz's "Spokane flood" outraged geologists six decades ago, partly because it seemed to flaunt catastrophism. The concept that Lake Missoula discharged regularly as jökulhlaups now accords Bretz's catastrophe with uniformitarian principles.

INTRODUCTION

Catastrophic floods have sold poorly in the market of ideas. The notion of even one great "Spokane flood" (Bretz, 1923) ignited a vehement controversy in American geology. Despite unambiguous and well-articulated field evidence, it took decades of sometimes strident debate for geologists generally to accept Bretz's "outrageous" hypothesis of catastrophic flooding from Pleistocene glacial Lake Missoula, Montana (Bretz, 1969; Baker, 1978c; Gould, 1978). I recently introduced a new development: the late Wisconsin Missoula floods were 40 or more separate outbursts (jökulhlaups) from a self-dumping glacial lake (Waitt, 1980b). This hypothesis has kindled new debate, not so much in the customary arena of Washington's Channeled Scabland (Fig. 1) as in backflooded tributaries just off the main flood throughways. Did the great late Wisconsin Lake Missoula floods number only one, two, or a few—the conventional view—or were there scores of enormous jökulhlaups from a periodically self-dumping lake?

The scores-of-floods hypothesis has been debated since it was introduced in 1978. A sparseness of evidence at some localities has troubled not only participants of recent field trips (Waitt, 1980a, 1982a, 1983) but also other investigators (Patton and others, 1979; Bjornstad, 1980, 1982; Bunker, 1982; Baker, 1983). Yet new evidence confirms the scores-of-floods hypothesis. This report (1) summarizes the first evidence for many floods and presents new, independent evidence that glacial Lake Missoula discharged episodically and repeatedly; (2) shows quantitatively how the great ice dam impounding glacial Lake Missoula became repeatedly buoyant and thus allowed catastrophic discharge episodically; (3) shows that the lake should have filled at the rate indicated by numbers of interflood varves, an average period between floods of a few decades; (4) answers deductive problems; and (5) refutes published challenges to my hypothesis of dozens of Missoula floods.

Until recently, almost all late Wisconsin flood effects in the Columbia River valley were thought to have resulted from only a very few floods (Bretz and others, 1956; Bretz, 1969; Waitt, 1977; Baker, 1973, 1978b; Mullineaux and others, 1978). I found geomorphic evidence that the northwestern segment of the Columbia River valley conveyed the deepest of the Missoula floods (Fig. 1) (Waitt, 1977, 1980a, 1982b). Although the valley carried every flood that made it past the Okanogan lobe, geomorphic effects of a later small flood are difficult to distinguish from effects of the wane of an earlier huge flood.

Floods are reliably counted only in stratigraphic sections. Tributaries of the Columbia were ideal settling basins for floodborne suspended load; they preserve rhythmic sequences of graded sand and silt beds by which pulses of flood sedimentation can be counted bed by bed. Having noted rhythmic bedding in valleys marginal to the Channeled Scabland, Bretz (1929, p. 539) asked, "Is not some kind of rhythmic pulsation in water supply recorded in these strata?" His last paper, however, stated that "these backflood deposits remain the least understood of all the phenomena that record the Missoula floods" (Bretz, 1969, p. 514). In 1978 I found evidence of subaerial environments between some graded beds, indicating that they were deposits of *separate* floods; I argued that during the last glaciation alone there had been ~40 separate floods from glacial Lake Missoula (Waitt, 1980b).

The rival notion that the slack-water beds represent nearly continuous lacustrine deposition has long precedent. The cyclic bedding has been attributed to diverse fluctuating-lake environments (Allison, 1933; Flint, 1938; Lupher, 1944; Newcomb and others, 1972). Recent investigators have attributed these deposits to one or a few Missoula floods (Bretz and others,

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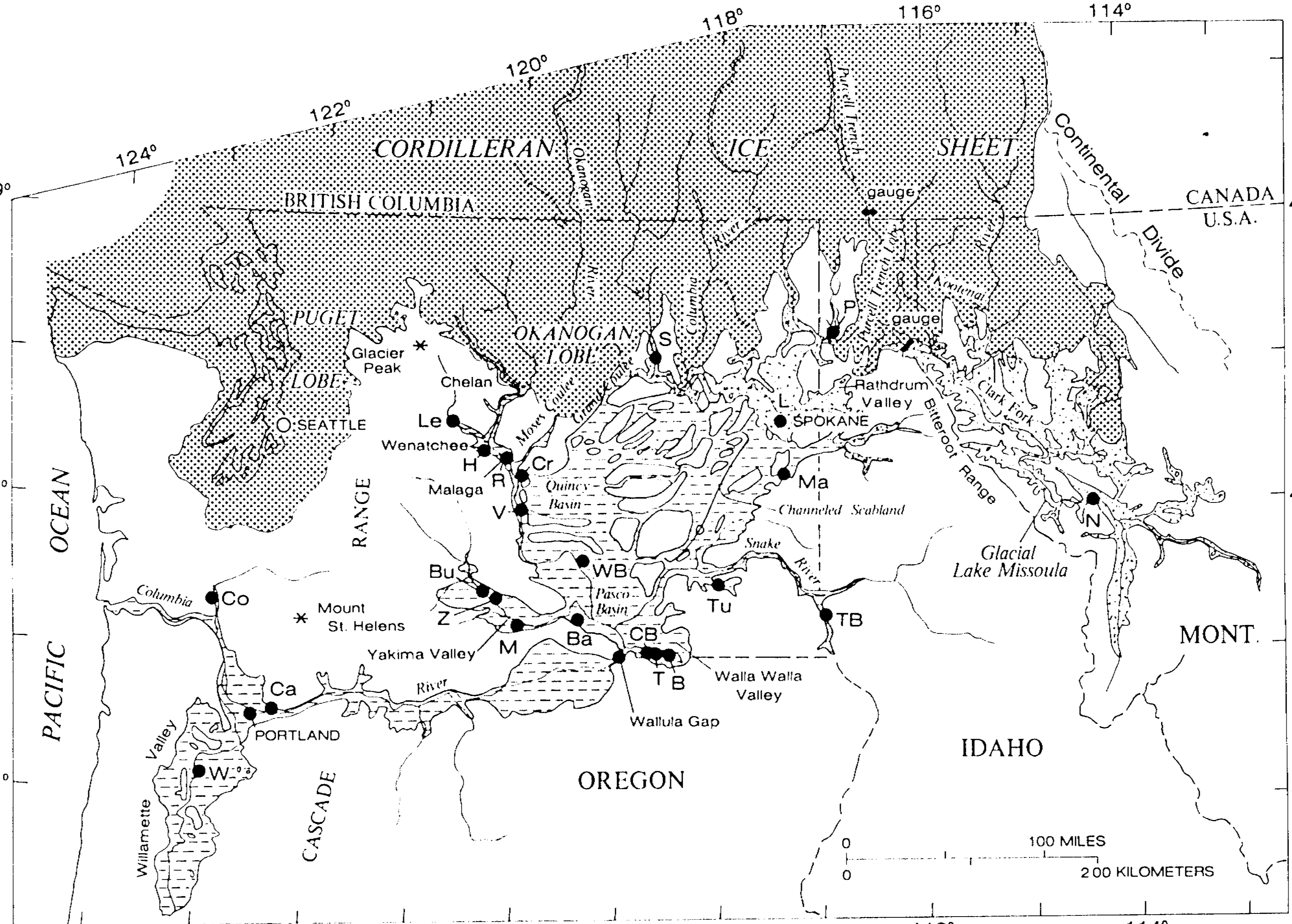


Figure 1. Map of Columbia River valley and tributaries. Small dots show maximum area of glacial Lake Missoula east of Purcell Trench ice lobe and maximum extent of glacial Lake Columbia east of Okanogan lobe. Lined pattern shows area that, besides these lakes, was swept by the Missoula floods. Closed circles indicate sites of bedded flood sediment discussed in text: B = Burlingame canyon; Ba = Badger Coulee; Bu = Buena; Ca = Camas; Co = Cowlitz valley; Cr = Crescent Bar; CB = Cumings Bridge; CR = Castle Rock; H = Horse Lake Canyon; L = Latah Creek; Le = Leavenworth; M = Mabton; Ma = Malden; N = Ninemile Creek; P = Priest valley; R = Rock Island bar; S = Sanpoil valley; T = Touchet; Tu = Tucannon valley; TB = Tammany bar; V = Vantage; W = Willamette valley section; WB = White Bluffs; Z = Zillah.

1956; Richmond and others, 1965; Bretz, 1969; Hammatt, 1977; Waitt, 1977; Baker, 1978a, 1983; Mullineaux and others, 1978) and attributed the rhythmic bedding to hydraulic surging *during* a flood (Baker, 1973; Carson and others, 1978; Patton and others, 1979; Bjornstad, 1980; Bunker, 1982).

The conventional many-rhythmites-per-flood hypothesis claims that most or all contacts between major beds represent only hours and that the depositional environment was continuously subaqueous; the new one-rhythmite-per-flood hypothesis claims that decades separated emplacement of each major graded rhythmite. Critical to choosing between the hypotheses is only evidence and reason that unambiguously favors one or damages the other.

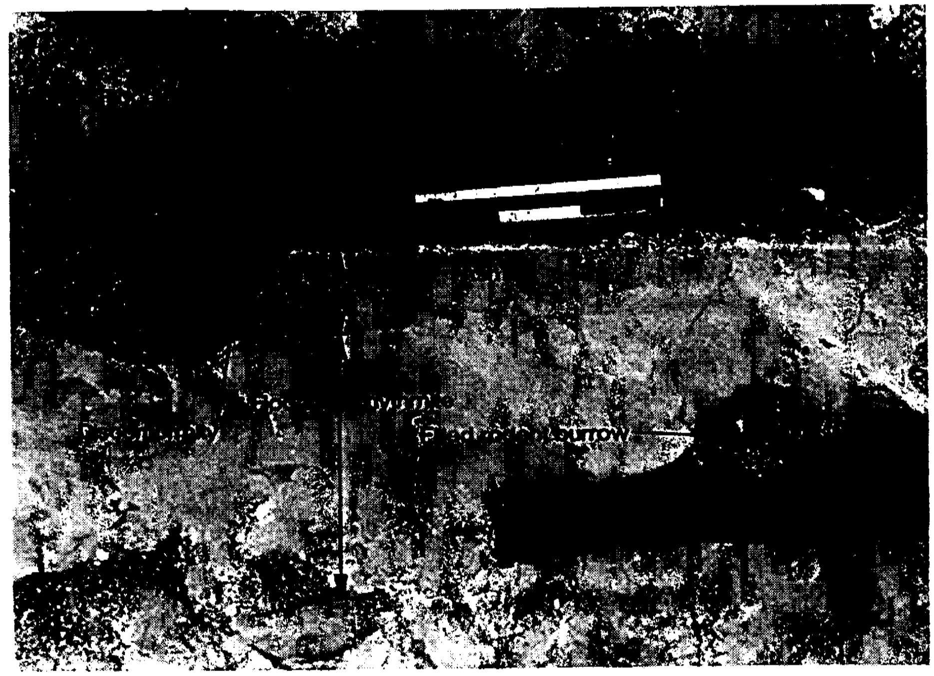


Figure 2. Massive loess overlying flood-laid zone *e* of rhythmite top at Mabton. White lamina at top of loess is basal unit of Mount St. Helens set-S ash (see Fig. 3).

EVIDENCE FOR DOZENS OF FLOODS

The Columbia River valley, the Channeled Scabland, and other flood throughways contain spectacular water-eroded landforms and enormous bars of flood gravel. Counting floods is impossible in these bizarre floodways, where one flood tended to obliterate effects of previous floods. Hydraulically ponded water flooded back up and slackened in dead-end tributaries, depositing suspended load (Bretz, 1929, 1930). This sediment was little disturbed by succeeding floods; a younger flood veneered older deposits, preserving rather than obliterating them.

I find diverse evidence of lengthy breaks in deposition between the successive graded beds in rhythmically bedded slack-water deposits, and therefore I argue that every major graded bed represents a separate outburst of glacial Lake Missoula. The following lists some of the field evidence on which the one-rhythmite-per-flood hypothesis was first based (Waitt, 1980b).

1. Channels were eroded into some rhythmites and infilled by slopewash sediment before burial by the next rhythmite.

2. Loess discontinuously separates many graded rhythmites (Fig. 2).

3. As much as 30 m below the surface, abundant rodent burrows have fillings as consolidated as the enclosing sediment (Fig. 2). Small rodents, which can burrow no deeper than 2 m, must have repeatedly repopulated the sediments during their accumulation.

4. A couplet of ash beds from two separate explosive eruptions of Mount St. Helens is sandwiched between two graded rhythmites (Fig. 3). The base and middle of each ash is pure, yet the top of each is reworked by wind or sheetwash.

Figure 3. Prominent ash couplet between successive graded backflood beds near Mabton. In addition, tops of underlying graded bed and overlying graded bed are each capped by ash laminae (arrows). Prominent couplet and the lowest ash lamina constitute the set-S triplet reported at many localities to the north and east. Top of each member of the prominent couplet is reworked with loess. Foreset bedding in coarse basal bed dips upvalley (right).

5. Shells from shallow fresh water were redeposited in water-laid dunes at the bases of some rhythmites. Decades were required for the shells to accumulate in a nearby shallow pond before an inrushing flood reworked them.

6. The sedimentary motif of a backflood rhythmite is normal grading from sand to silt and an upward succession of massive, plane, ripple-drift to draped, and massive structures—designated as zones *b, c, d,* and *e,* analogous to, yet different from, divisions *b* through *e* in turbidites. The silt of rhythmites can settle if turbulence ceases for minutes (Bretz, 1929, p. 540), and the vertical sequence of bedforms can form in hours (Ashley and others, 1982). This record of a waning current is cyclically repeated in successive beds of regular thickness (Figs. 4–7). Many of the beds were each demonstrably formed by a separate flood. Each of 40 other similar beds therefore must have been formed by a separate flood, there being no contrary evidence.

7. A different sedimentary motif of the rhythmic bottom sediments of glacial Lake Missoula comprises a basal silt grading up to clayey varves (Fig. 8), each rhythmite thus being the record of a lake *cycle* that was decades in duration. At least 40 such superposed graded cycles show that during the last glaciation glacial Lake Missoula slowly filled and rapidly drained at least 40 times.

NEW EVIDENCE

Not only has field evidence recently augmented these and other points, but entirely new evidence confirms the hypothesis of one-bed-per-flood and is hostile to the hypothesis of many-beds-per-flood.

Rip-up Clasts

Angular clasts of rhythmite-top or inter-rhythmite mud lie within the coarse bases of flood-laid rhythmites at Latah Creek and Sanpoil valley, beds showing other evidence of violent emplacement (see below). Had several rhythmites been deposited by one flood, the silty tops could not have become dewatered and coherent enough to be eroded as clasts and redeposited during that flood. The clasts imply that the rhythmite-top and overlying sediment had dried, or, in the case of clayey sediment, had long been submerged in lakes before the next flood swept in. The clasts are evidence of long interludes between episodes of flood deposition; as they lie in successive flood-laid beds, there must have been many interruptions during accumulation of the beds.

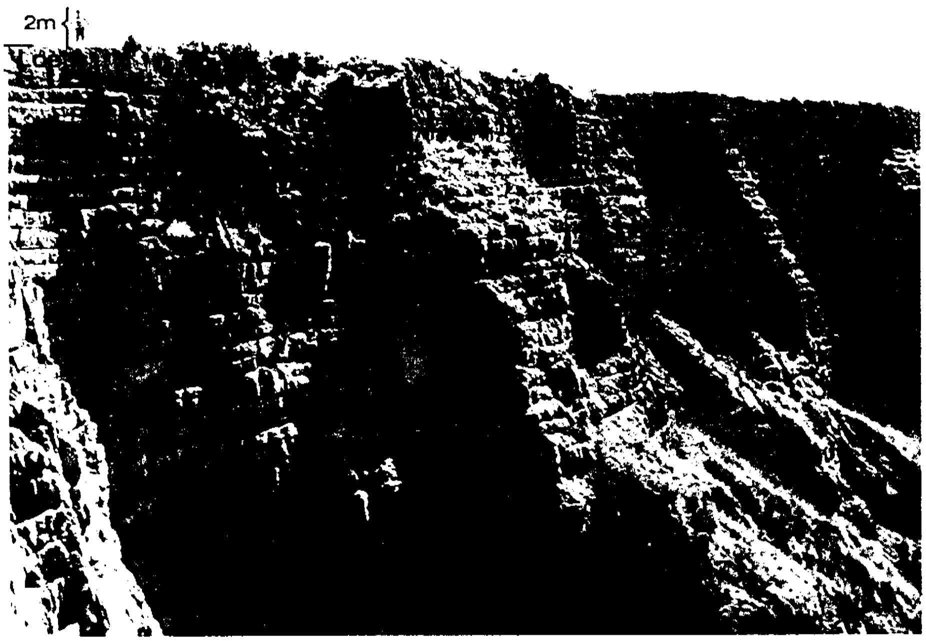


Figure 4. View of ~39 graded rhythmites exposed at Burlingame canyon, Walla Walla valley. Mount St. Helens set-S ash at arrow, overlain by 11 flood-laid rhythmites and capped by loess.

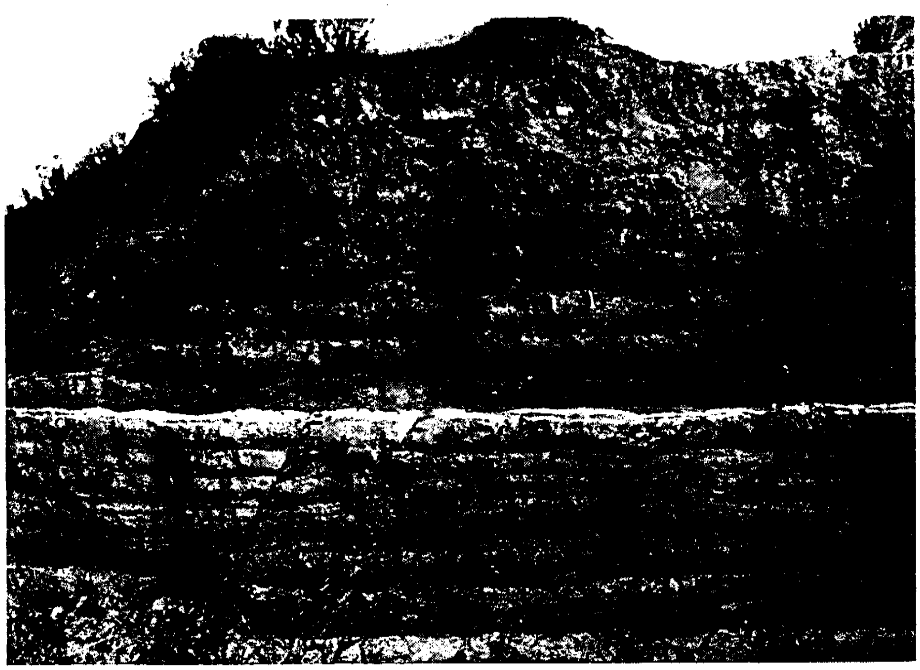


Figure 5. About 17 graded rhythmites near Mabton, lower Yakima valley. Rhythmite topped by Mount St. Helens set-S ash is overlain by eleven rhythmites, of which nine are visible here. Section is capped by ~1 m of Holocene loess. Shovel handle = 43 cm.

Ash Layers

In addition to the prominent ash couplet that overlies one of the rhythmites in southern Washington (Figs. 3–6), two fine-ash laminae are intercalated within a rhythmite sequence near Mabton (Fig. 5). One lamina overlies the rhythmite below that topped by the ash couplet; the other overlies the rhythmite above that topped by the couplet (Figs. 2 and 3). The two

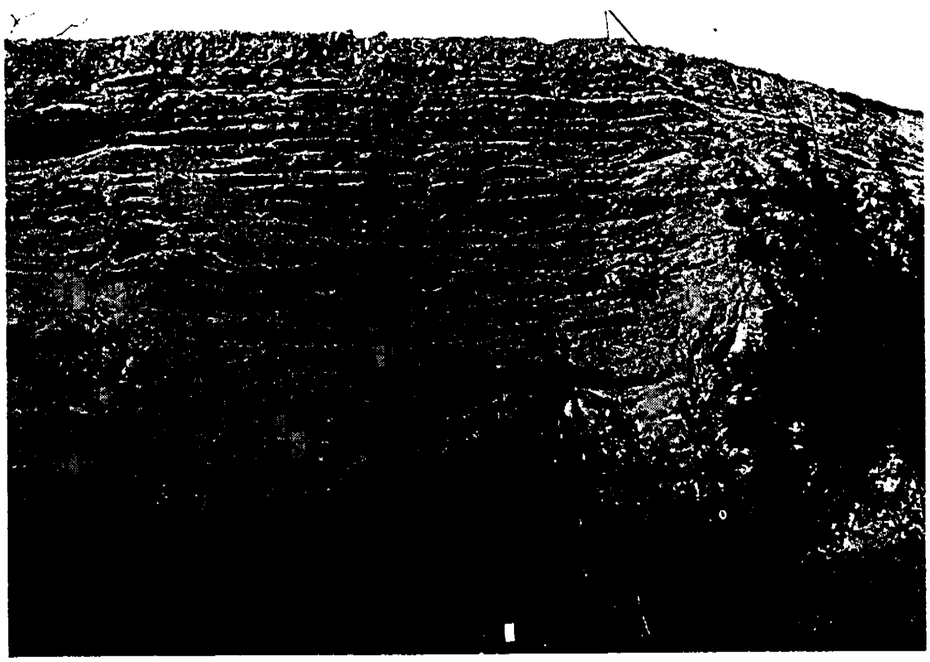


Figure 6. About 25 graded rhythmites near Zillah, lower Yakima valley. Mount St. Helens set-S ash couplet at arrow overlain by 4 thin rhythmites topped by Holocene loess. Visible part of nearest two fence posts at top of exposure is ~1 m.

Figure 7. Succession of graded beds of the Willamette Silt overlying preflood sediment along the Willamette River near St. Paul, Oregon. Glenn (1965, p. 87–99) gave petrographic evidence that these rhythmic beds were emplaced by backflood from the Columbia River valley, and he counted here "at least 40 distinct beds." Photograph by J. L. Glenn.

ash laminae are only 1 mm or less thick, yet each is uncontaminated. It is impossible that the fine particles of these trifling layers could have accumulated uncontaminated at the base of turbid flood water that was emplacing the enclosing beds in rapid succession. Instead, the three ash horizons are evidence of a long break between each of four successive rhythmites: each bed accumulated during a separate flood.

About 16 other nearly identical rhythmites are exposed at the Mabton section, half above the ash-topped rhythmites and half below. Many are separated from each other by evidence of a lengthy break between rhythmites, such as discontinuous loess (Fig. 2) or shell-rich dunes (Waitt, 1980b, Fig. 10). Each of the ~20 successive graded beds at Mabton must therefore record a separate, stupendous backflood up the lower Yakima valley.

Clayey Lacustrine Beds between Flood-Laid Beds

Certain bodies of coarse flood-bedload gravel along the northwestern segment of the Columbia River contain graded interbeds of fine sand to silt (median grain sizes determined in field by comparison to standards; terminology from Folk, 1974). The interbeds reveal repeated sharp drops (almost to nil) in transportational competence as the strata accumulated.

Rock Island Bar, Central Washington. One of the flood-gravel bodies was built into Columbia valley out of Moses Coulee (Fig. 1), a floodway carved into the Columbia River Basalt prior to the maximum stand of the Okanogan ice lobe (Bretz and others, 1956; Hanson, 1970; Waitt and Thorson, 1983). Because the Okanogan lobe blocked the Columbia farther upvalley, floods could not sweep down the valley simultaneously with those from Moses Coulee, which therefore spread an enormous fan of gravel across the Columbia, blocking it.

Rock Island bar, an upvalley part of the fan, comprises four gently upvalley-dipping beds of basaltic (Moses Coulee–derived) gravel the tops of which grade up from fine gravel through sand to silt (Fig. 9). The normal grading and upward succession of sedimentary structures closely resembles that of a well-formed rhythmite in the lower Yakima or Walla Walla valley. The graded bed atop the lowest gravel bed is capped by at least 37 graded silt-to-clay couplets identical to classic varves (Fig. 10) (compare Antevs, 1951; Ashley, 1975; Gustavson, 1975). The top of the varved bed is truncated by a minor flood-scoured disconformity at the base of the next overlying bed. The fan apparently dammed a lake in the Columbia valley that lasted four decades between two separate floods down the coulee.

Of the other three graded interbeds higher in Rock Island bar, only the lowest is capped by varves, and that by only three. Yet each of the sand-to-silt beds atop the four basalt-gravel beds shows a similar normal grading and an upward succession of rhythmite zones *b, c, d,* and *e.* The two higher graded beds are nearly identical to the two lower varve-capped beds: the four beds must record four separate floods down Moses Coulee.

These four floods are only part of the record of late Wisconsin Missoula floods along that segment of the Columbia River (Waitt, 1982b). The basalt-gravel and rhythmite section at Rock Island bar is overlain by 11 m of thick-bedded, very fine sand and silt that lacks thin bedding, laminations, and clay beds—unlike normal lacustrine sediment in central Washington but similar to flood-slack-water sediment. This fine flood-laid sediment probably accumulated after Moses Coulee itself became blocked by the advancing Okanogan lobe and the westernmost floodway became Grand Coulee, the floods of which reached Rock Island bar only by long-distance backflooding (Fig. 1). This fine bed is in turn overlain by mixed-lithology, upvalley-derived boulder gravel embellished by giant current dunes, evidence that at least one large flood flowed down the valley after the Okanogan lobe retreated to north of the Columbia valley.

The number of separate floods represented by the stratigraphy at Rock Island bar is at least six (four down Moses Coulee, at least one down Grand Coulee, one down the Columbia valley). Moreover, geomorphic relations near and upvalley of Wenatchee (Waitt, 1982a, 1982b) indicate one or more 300-m-deep floods down the Columbia before the Moses Coulee interval; at least two small floods also swept down the Columbia after the flood that topped Rock Island bar. The least number of floods in the area is thus nine. The 11-m thickness of silt backflooded from the Grand Coulee suggests several additional floods.

Horse Lake Canyon, Central Washington. A recently cut road in lower Horse Lake canyon, a Columbia River tributary west of Wenatchee (Fig. 1), exposes a nearly continuous, 60-m-thick section of thin-bedded, laminated, nonvarved fine sand to silt, a record of a long-lived lake dammed in the Columbia by a huge late Pleistocene landslide (Waitt, 1982b). The absence of sharply graded beds and rhythmic bedding suggests that the lower 45 m of section predates the catastrophic backfloods.

The upper 15 m of section consists of about 25 granule-gravel to coarse-sand beds whose ripple-drift laminae show that depositing currents flowed *up*valley. Each coarse bed grades up into very fine sand sharply overlain by several centimetres of nonvarved, laminated very fine sand to silt (Fig. 11). The lack of varve disallows counting the duration of these lacustrine intervals, yet they do bespeak a long-term lake between successive backfloods, not mere pauses between pulses of one flood. The upper part of the section thus reveals ~25 separate backfloods, each followed by a lengthy but untimed lacustrine interval. This section complements the less complete, more erosional "proximal" section nearby at Rock Island bar.

Northern Idaho and Washington. Large ice-dammed Pleistocene lakes in northern Idaho and northeastern Washington were periodically engorged by sediment from the Lake Missoula floods (Fig. 1) (Waitt and Thorson, 1983). Beds of bedload gravel to coarse sand and beds of flood-suspended fine sand to silt alternate with beds of lacustrine mud, each containing 20 to 55 silt-to-clay varves. Gravel and sand beds with upvalley-directed paleocurrent indicators at Latah Creek valley (Fig. 12) resemble "proximal" rhythmites in southern Washington, such as downsection at Mabton and Touchet (Fig. 5) (Waitt, 1980, Fig. 6); graded sand and silt beds with upvalley paleocurrent indicators in the Priest River valley (Fig. 13) closely resemble "distal" rhythmites in southern Washington, such as at Zillah and upsection at Burlingame canyon and Mabton (Figs. 4–6). (Data from northern Washington and Idaho are more fully analyzed by Waitt, 1984.) The graded beds in northeastern localities are silt poor; those in southern Washington, silt rich. From northeastern Washington, the floods swept over loess-covered and lacustrine tracts in the Channeled

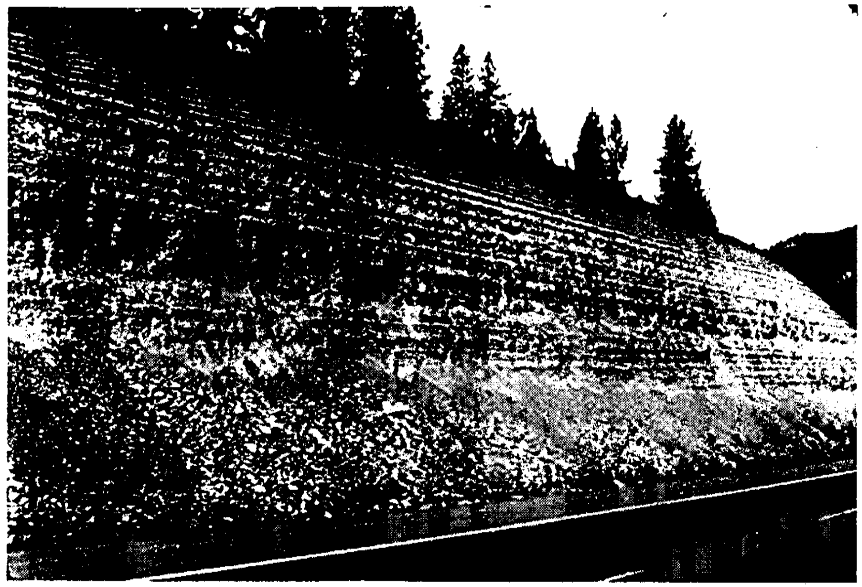


Figure 8. Lake Missoula bottom sediment in Clark Fork valley, Montana near confluence of Ninemile Creek. In each rhythmite, sand, silt, and compound varves (light colored layers) grade up to clayey simple varves (dark layers). Photograph shows ~30 of the 40 or more rhythmites here.

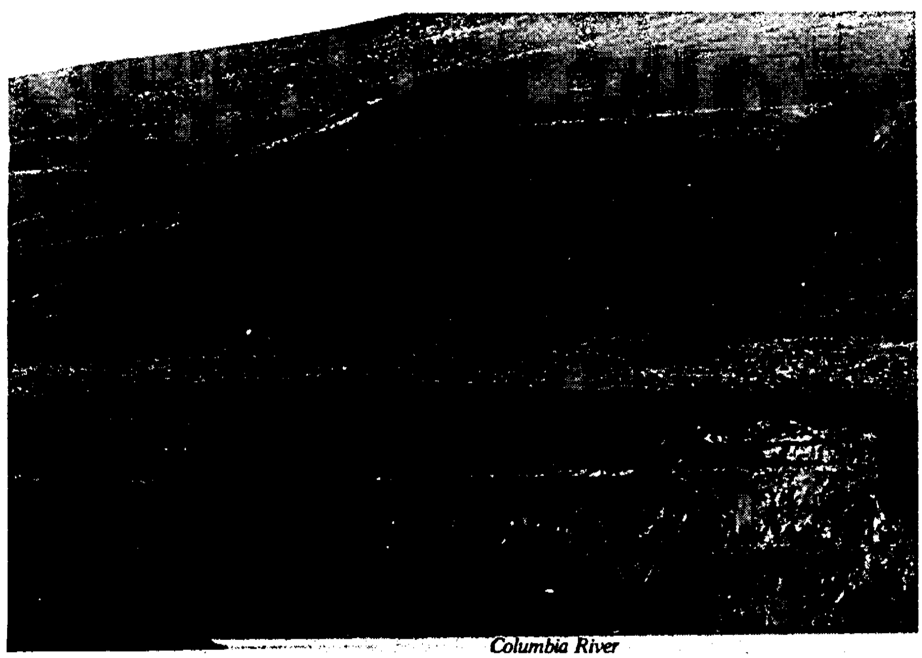


Figure 9. Section at Rock Island bar 18 km southeast of Wenatchee. Four basalt-gravel beds shed *up* the Columbia valley (right) from Moses Coulee are each topped by a graded sand-silt bed. Section is overlain by bedded flood-laid silt, which is overlain by *down*valley-moved flood gravel embellished by giant current dunes thinly capped by Holocene loess. Circle shows view of Figure 10.

Figure 10. Rhythmite atop lowest graded bed at Rock Island bar, showing zones, *b, c, d,* and *e*. Flood-laid bed overlain by section of at least 37 silt-to-clay varves; top of varved bed is eroded and sharply overlain by the next-younger flood-laid bed.

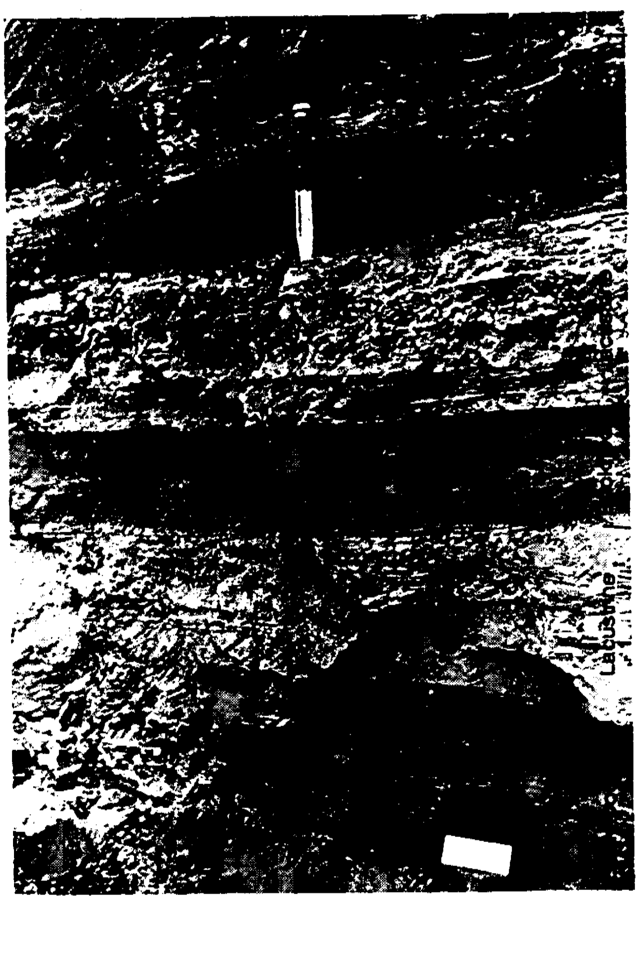


Figure 11. Succession of 3 of the 25 graded gravel-to-sand beds topped by laminated silt, part of the upper 25 m of Horse Lake canyon section.

Scabland and Columbia River valley, becoming thus silt-charged only south or west of Spokane. In the north, beds comprising tens of clayey varves alternate with 16 or more backflood sand or gravel beds that closely resemble backflood rhythmites in southern Washington; here is unambiguous evidence that decades separated successive, colossal floods from glacial Lake Missoula.

In deposits of the Sanpoil arm of glacial Lake Columbia (Fig. 1), backflood (upvalley paleocurrents) beds alternate with silt-clay beds, each comprising tens of varves (Fig. 14). Atwater (1983, 1984) detailed both "proximal" and "distal" flood facies and a composite section evincing at least 50 and perhaps >80 abrupt interruptions of the prevailing glaciolacustrine environment (varved beds) by catastrophic backfloods. Rhythmically bedded sequences that puzzled earlier workers along the adjacent Columbia River valley show similar alternations between floods and glacial lake (B. F. Atwater and V. L. Hansen, 1983, personal commun.). These periodic coarse beds are in valleys that could not have escaped the Missoula floods.

The only water body voluminous and high enough to vigorously flood the various glacial lakes in northern Idaho and Washington was glacial Lake Missoula (Waitt and Thorson, 1983, Table 3-1). The dispersed stratigraphic sections thus reveal the behavior of Lake Missoula and must be cognate with rhythmite sections in Montana, southern Washington, and northern Oregon.

Other Rhythmic Beds

If scores of separate, stupendous jökulhlaups each typically produced a graded bed in backwater areas, rhythmic successions of graded beds should be widely distributed through the region. Only a few backflood valleys have been examined since the scores-of-floods hypothesis was published in 1980. Rhythmic beds, however, continue to be discovered—those in the Priest, Spokane, Latah, Sanpoil, and upper Columbia valleys have come to light only recently.

Snake Valley Near Lewiston. Overlying Bonneville-flood gravel (see below) in the Snake valley at Tammany bar near Lewiston, 13 relatively thick graded beds underlie 8 thinner ones (Fig. 15), an upsection thinning of beds consistent with a regional pattern (compare Figs. 4–8). These rhythmic beds each consist of basal coarse sand to granule gravel overlain by a graded sand-to-silt bed (Fig. 16). The basal coarse facies consists of angular fragments of locally derived basalt, beds whose small foresets dip *up* the Snake valley. These and other similar deposits are clearly of the Missoula backflood(s), as

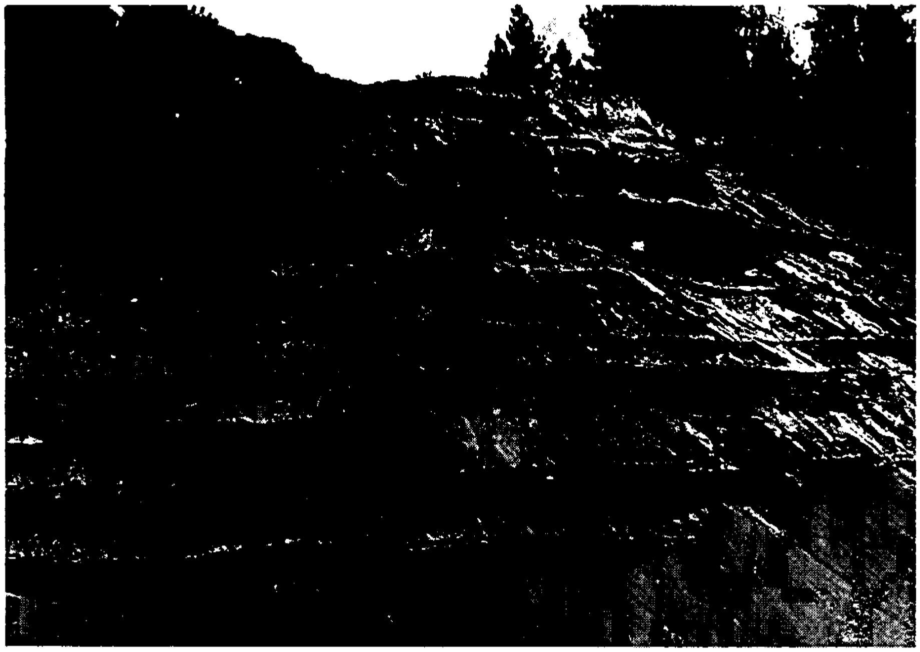


Figure 12. Nine of the 16 successive gravelly sand, flood-laid beds exposed in Latah Creek valley, each overlain by a thin bed of varved clay (v). Foreset beds dip upvalley, which is to the right and out of plane of photograph.

Figure 13. Beds of varved clay (dark bands) alternating with flood-laid beds of sand (light colored) in Priest River valley, northern Idaho. Eight flood-laid beds are visible, but entire section exposes 14 such beds. Details of section discussed by E. H. Walker (1967) and Waitt (1984).

argued by Bretz (1929, p. 419–427). I did not find proof of nonflood conditions between the graded beds. Yet these beds are so similar to those at Burlingame canyon, Mabton, and Priest valley, where each graded bed is demonstrably the deposit of a separate flood, that they cannot but record the same history. Rhythmites at Tammany bar typically have a zone of down-valley-directed, ripple-drift laminae above the basal upvalley-directed, foreset laminae (Waitt, 1983). This consistent sequence records an upvalley-rushing flood, a single cresting, and finally, downvalley draining as the flood ebbs (compare Waitt, 1980b, Fig. 12).

Other Valleys. Limited space precludes discussion of every known stratigraphic section that gives evidence of separate floods, but the regional dispersal of such evidence (Fig. 1) is important. In addition to the localities discussed above, the following valleys all contain sections showing rhythmically bedded slack-water sediment or contain fine slack-water sediment interbedded with coarse, tractive-load flood sediment: Wenatchee valley, lower Tucannon valley, northeastern Channeled Scabland at Malden, and the Columbia valley near Crescent Bar, Vantage, White Bluffs, Camas, and Portland (Fig. 1). Bedded silt containing erratics rafted from northern Idaho lies in all major tributaries of the Channeled Scabland and the Columbia valley as far west as the lower Cowlitz valley. Definitive evidence of nonflood deposits between rhythmites is not known at every exposure (subtlety of evidence is explained below), but the flood rhythmites in these several valleys are nearly identical to those in other localities where unmistakable nonflood deposits are sandwiched between successive rhythmites. The deposits of successive floods thus lie in backwater tributaries scattered all the way from the ice dam to the Pacific Ocean.

Regional Relations

Figure 17 illustrates inferred correlations between the graded flood rhythmites in southern Washington, those in northern Washington and Idaho intercalated with varves, and the varved bottom-sediment rhythmites of glacial Lake Missoula in Montana. Nonflood times recorded by the varved Lake Missoula cycles are also recorded by the varves of glacial lakes in northern Washington and Idaho, but they are represented only by hiatuses or minor eolian beds in southern Washington. Conversely, the brief, colossal floods recorded by graded beds in northern and southern Washington are represented only by obscure hiatuses in the Lake Missoula rhythmites. Most stratigraphic sections show only 20 or fewer rhythmites, because the top of the section is eroded (Rock Island bar, Latah Creek), because the base is not exposed (most sections), because higher-altitude sections escaped the smaller floods (Zillah, Tammany bar), or because glaciers or other processes dominated during part of late Wisconsin time (Priest valley). The conceptual Figure 17 depicts effects that must be contemporaneous, but it does not imply that particular beds can be readily correlated across the region.

ONE GRADED BED PER CATASTROPHIC FLOOD

Participants in recent field trips have debated over the sparseness of evidence for scores of floods, and critics have made their most serious charges in the backflooded valleys of southern Washington. As a Missoula flood backflowed up these tributaries, an abrupt inrush and rapidly accelerating current was followed by gradually waning currents as the water ponded deeply, crested, and then subsided. The emplacement of a graded flood-laid bed has been likened to a turbidity current (Baker, 1973). Although the analogy is imperfect (Waitt, 1980b), a turbidity current is an energetic, bottom-hugging, sediment-laden flow that arrives suddenly in a still environment and then gradually wanes, leaving one sharply graded bed (Kuenen, 1967). The devastating pyroclastic density current off Mount St. Helens volcano on 18 May 1980 deposited one graded bed of gravel and sand topped by silt (Waitt, 1981); the distinct upward and outward grading is similar to that of a proximal-to-distal turbidite (for example, see R. G. Walker, 1967) and of a proximal-to-distal Missoula-flood rhythmite (Waitt, 1980b, Fig. 3). A turbidity current, a pyroclastic density current, and a Missoula flood is each a short-lived, energetic, ground-hugging flow that sweeps variously sized particles from higher to lower altitude. In each flow, an early high-energy environment is followed by progressively lower-energy environments and then by quiescence. What deposit is expected of a Missoula flood in a back-water area except a single graded bed?

The rival explanation of rhythmicity is that multiple hydraulic surges during one flood produces multiple, major graded beds (Baker, 1973; Patton and others, 1979; Bjornstad, 1980). The supposed cause of such surges (abrupt local changes in flood-surface level), however, could not have dominated current velocity and sedimentation at the base of deeply ponded water. An inrushing flood of hundreds of cubic kilometres on the one hand and transient intraflood surging on the other are wholly different processes; transportational competence at the base of the two flows must differ by orders of magnitude. The proposition of many graded beds per Missoula flood is unfounded.

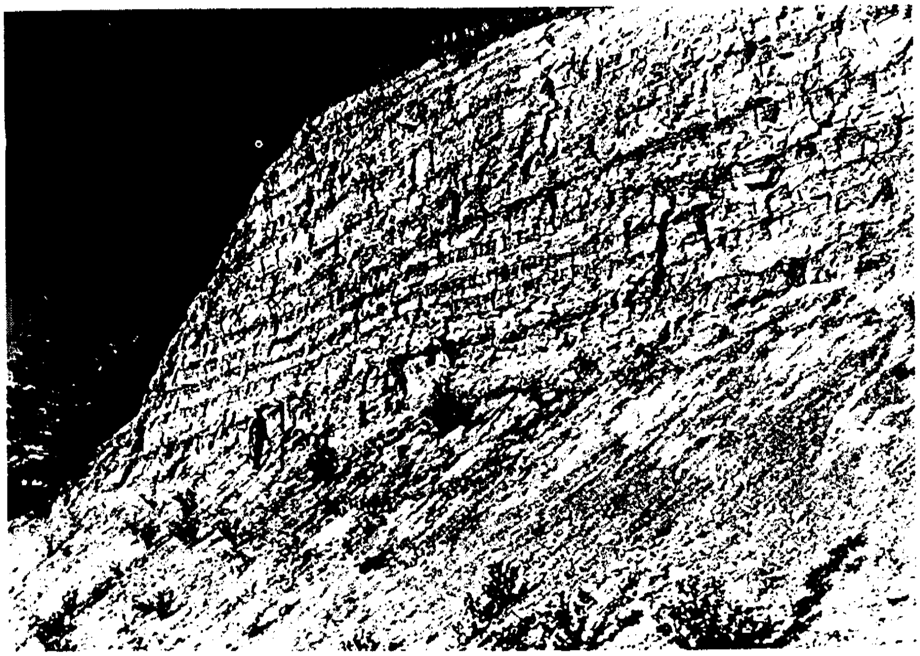


Figure 14. Section in Manila Creek valley, a tributary of lower Sanpoil valley, showing about 15 flood-laid sand beds (light colored layers) intercalated with beds of varves (dark layers).

Figure 15. Section of Missoula-flood beds overlying Bonneville-flood gravel at Tammany bar in Snake River valley near Lewiston. Missoula-flood beds consist of basal gravel topped by graded sand-to-silt bed. Total thickness shown is ~6 m.

Sparseness of Nonflood Evidence between Flood Beds

During field trips to rhythmite successions in Washington or Idaho (Waitt, 1980a, 1982a, 1983), a deductive question is often asked: If each graded bed at Burlingame canyon, Mabton, and Tammany bar (Figs. 4, 5, 16) represents a separate flood, and if decades intervened between emplacement of each graded rhythmite, why is evidence of nonflood deposits, subaerial exposure, or bioturbation so inconspicuous between them? In the broad valleys east of the moisture-grabbing Cascade Range, mean-annual precipitation is only 19 to 41 cm, delivered as gentle rain or snow (U.S. National Weather Service data 1931–1970 for Walla Walla, Kennewick, and Yakima). Slopes are nearly level at most rhythmite exposures, and the sediment is well-sorted, permeable sand and silt uninterrupted by impervious clay beds. Precipitation therefore seeps in with minor runoff and gullying. On gentle slopes, the regional postflood loess blanket is typically ungullied despite as much as 13 millennia of continuous exposure, and thus a level rhythmite of permeable silt should not be channeled after mere decades.

Fierce windstorms in thinly vegetated south-central Washington transport silt and fine sand,

Figure 16. Missoula-flood rhythmites capping Bonneville-flood gravel at Tammany bar. Foresets in Bonneville gravel dip downvalley; those in channel within Missoula-flood beds dip upvalley. Shovel handle = 43 cm.

but material thus deposited during a few-year period is trifling. The 18 May 1980 ash layer from Mount St. Helens lay at the surface in 1984 only scarcely and locally veneered by eolian silt. Holocene loess in the region buries the 7,000-yr-old Mazama ash locally by 1 m but generally by much less. Eolian silt thus generally accumulates <1 cm in 7 decades. A thin layer of massive silt atop nearly identical rhythmite-top silt from which it was derived is scarcely visible. Yet a careful search at the Mabton and other rhythmite sections reveals that massive loess thinly and discontinuously separates water-laid rhythmites (Fig. 2).

Small-root casts, insect burrows, and other signs of bioturbation are conspicuous only where they juxtapose white ash against brown silt (Waitt, 1980b; Bunker, 1982), but most such tiny structures are obscure because rhythmite tops are monotone and nearly massive. There is no evidence of weathering at rhythmite tops, because only decades separated successive floods. Quartzose silt of the rhythmite tops could not oxidize rapidly in the semiarid climate, and even slight eolian effects diluted incipient weathering.

In some marine-turbidite basins, sedimentation by the normal deep-sea environment is so slow and the sediments so fine that nonturbiditic sediment is scarcely seen at the fine-grained tops of successive distal turbidites (Hesse, 1975). The nonturbiditic sediment is easily overlooked, even though it may represent almost all of the time recorded by a stratigraphic section. The preserved depositional record of most volcanic centers is similarly uneven. At Mount St. Helens (Mullineaux and Crandell, 1981), for instance, deposits of rare pyroclastic flows, air falls, lahars, and lava flows show little trace of the centuries or millennia between catastrophes. The flood-rhythmite sequences in southern Washington are scarcely unique in preserving so little evidence for the dominant, long-term, noncatastrophic, low-energy environment.

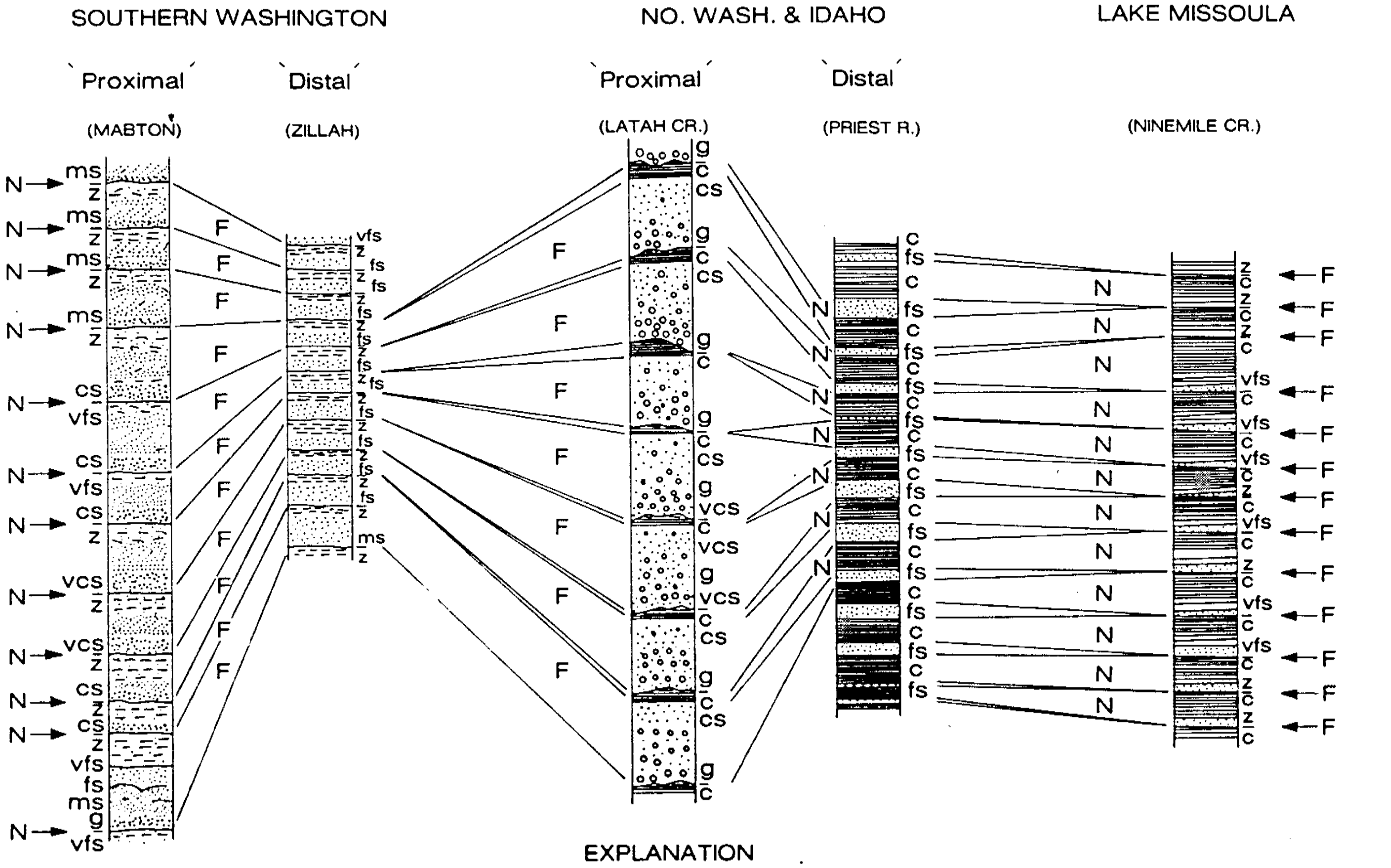
HYDROLOGY OF LAKE MISSOULA AND ITS ICE DAM

Water Budget of Lake

New planimetry of the Lake Missoula basin indicates that the maximum volume of the lake (at surface level = 1,265–1,280 m) was ~2,500 km^3 (R. G. Craig, 1983, personal commun.), one-sixth larger than formerly supposed. Water was contributed to glacial Lake Missoula (1) mainly by melt water from the vast Cordilleran ice sheet on the north, (2) by melt water from alpine glaciers to the east and south, and (3) by runoff from the nonglaciated, mountainous southern half of the drainage basin (Fig. 1). Most of the water was imported as ice over the northern drainage divide; much of that area the precipitation of which thus entered the lake is the Kootenai drainage basin upstream of a gauging station at the international boundary (Fig. 1). Any estimate of the water budget for the Clark Fork drainage during the glacial maximum must add at least the present mean-annual discharge of the Kootenai drainage at this gauge (10,490 ft^3/s) to that of a gauge on the lower Clark Fork (7,462 ft^3/s) (U.S. Geol. Survey, 1975, p. 14, 148). The combined mean discharge of 15.76 km^3/yr would take 159 yr to fill a maximum 2,500-km^3 glacial Lake Missoula. This figure, however, excludes drainage of the Purcell Trench and several drainage basins north of the Kootenai, the ice of which also ablated into glacial Lake Missoula. If these discharges are added, a maximum Lake Missoula would fill in <125 yr.

For the Great Salt Lake basin 700 km south of glacial Lake Missoula, McCoy (1981, Table 4.2) calculated that the rate of inflow required to maintain Pleistocene Lake Bonneville between about 16,000 and 14,000 yr ago was 2 to 3 times the present inflow (subtracting effects of drainage-basin changes). Evaporation per unit volume should have been less at Lake Missoula than at Lake Bonneville, for Lake Missoula lay at a cooler latitude and had a much lower ratio of surface area to volume. Therefore, twice the present combined discharge of the Clark Fork, Kootenai, and more-northern drainages is a conservative estimate of the average net inflow to glacial Lake Missoula between 16,000 and 14,000 yr ago.

A discharge of twice the present combined discharge of the Clark Fork and Kootenai Rivers alone would fill a maximum glacial Lake Missoula in ~80 yr; if drainage farther north is added, the lake would fill in <65 yr. A lake of half-maximum volume would fill in <40 yr. The maximum number of varves between successive backflood beds in northern Washington and Idaho indicates an interflood period of two to six decades, an average of three to four. The average number of varves within bottom-sediment rhythmites of the Missoula basin is ~30; the range 10 to 60 (Chambers, 1971). The counted varves provide actual or minimum-limiting times between floods, for a varve may not be preserved for each interflood year. The average rise of Lake Missoula deductively inferred from the rate of lake filling is compatible with the three to four decades between successive jökulhlaups counted from varves between successive rhythmites.



EXPLANATION

Grain Size

c = Clay + silt
z = Silt
vfs = Very fine sand
fs = Fine sand
ms = Medium sand
cs = Coarse sand
vcs = Very coarse sand
g = Gravel

Environment

F = Flood
N = Nonflood

Figure 17. Inferred relations between rhythmites in southern Washington, northern Idaho, and western Montana.

Ice-Dam Hydrology

The only outlet of glacial Lake Missoula was through its ice dam. The lack of abandoned cataracts at potential spillover sites in the northern Bitterroot Range (Bretz and others, 1956, p. 1035) shows that the lake never rose enough to spill around the margin of the ice dam. The greatest depth of glacial Lake Missoula [upper limit of ice-rafted erratics (Pardee, 1942; Bretz and others, 1956)] against the maximum ice dam [reconstructed from crudely known upper limits of drift and glacial landforms (Alden, 1953; Richmond and others, 1965; Waitt and Thorson, 1983)] was somewhat less than the maximum thickness of the ice dam. The behavior of glacial Lake Missoula may be deduced from observed behavior and theoretical analyses of modern ice-dammed lakes (Thorarinsson, 1939, 1957; Embleton and King, 1968, p. 420–428; Post and Mayo, 1971; Björnsson, 1974). The glacial dams of all such lakes that lack alternate spillways are inherently metastable; many glacial lakes have drained catastrophically when the impounded water has risen deeply against the ice dam. Most or all such lakes drain before water rises enough to overtop the ice dam. There is neither field evidence nor theoretical reason that the huge glacial Lake Missoula, whose outlet was via the ice dam, should have behaved radically differently from small ice-dammed lakes.

In the following analysis of glacial Lake Missoula, I consider only a simple hydrostatic case. Other influences may cause the breach to occur at a lake level slightly lower than predicted only by hydrostatics: (1) a cantilevered lifting of the seal by the floating lakeward end of the ice dam (Nye, 1976), and (2) zones of lowered pressure at the glacier bed due to sliding over an irregular surface. These and other possible influences complicate a rigorous analysis, but they do not fundamentally alter the hydraulic relations addressed here. I consider hydrostatics only at the incipient stage of draining, and the equations thus ignore velocity of moving water, which becomes important when the flow becomes a flood. (A recent paper by Clarke and others, 1984, numerically simulates some aspects of water actively flowing through the ice dam.)

The physiographic characteristics of the glacial dam of Lake Missoula are drawn for the maximum stand (Fig. 18). As at Grímsvötn, Iceland, the water gradually rises against the ice dam; as it deepens, water progressively seeps beneath and makes buoyant the lakeward end of the dam (Thorarinsson, 1939; Björnsson, 1974). Subglacial drainage becomes possible when the hydrostatic pressure P_w of water from the lake approaches or exceeds the ice overburden pressure P_i at a critical seal at the glacier bed. Thus P_w ($=\rho_w g h_w$) must approach or exceed P_i ($=\rho_i g h_i$), which occurs when $h_w \geq 0.9 h_i$. (ρ = density; g = gravitational acceleration; h = thickness.)

The hydrostatic equilibrium can be evaluated

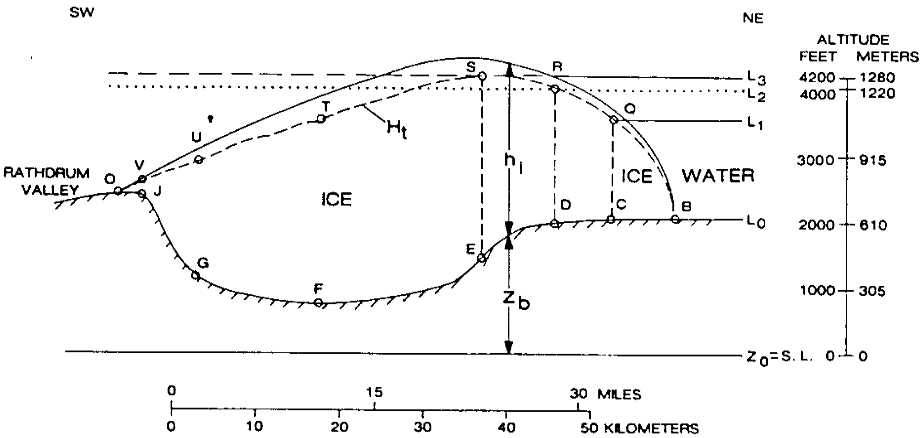


Figure 18. Schematic longitudinal section through ice dam (Purcell Trench lobe) impounding glacial Lake Missoula.

at the ice dam of Lake Missoula by principles discussed by Björnsson (1974), Nye (1976), and Clarke (1982). Nye (1976, equation 3) thus defines a potential Φ for water flow in a pressurized conduit at the glacier bed as:

$$\Phi = \rho_w g(z_b + \frac{\rho_i}{\rho_w} h_i),$$

where z_b = altitude of glacier bed, and h_i = ice thickness. Calculations are simplified by dividing through by $\rho_w g$ and defining a new potential, total head H_t (= $\Phi/\rho_w g$), expressed in units of altitude. Total head H_t, driving the water flow, is the sum of pressure head H_p (= $0.9h_i$) and altitude head H_a (= z_b):

$$H_p + H_a = H_t, \text{ or}$$
$$H_t = 0.9h_i + z_b \ .$$

Calculated values of H_t are lower at the base of the ice than at any point higher in the ice or at the ice surface: being denser than ice, water from the lake tends to flow to the glacier bed. Calculated along the glacier bed, total head H_t rises westward from the lake side of the dam but remains below the ice surface (Fig. 17). As the lake rises from level L_0 to L_1, the ice tongue whose head gradients are initially directed toward the lake (surface QB) becomes progressively "ungrounded" as the H_t of water in the lake (=lake-surface altitude) rises. The eastern limit of the seal along the base of the ice thus migrates westward from point B to point C. As the lake rises further to level L_2, overcoming the lakeward-inclined H_t surface RQ at the glacier bed, the seal is further narrowed, and its eastern limit becomes point D. Increasing hydrostatic pressure from rising glacial Lake Missoula thus progressively pries westward into and narrows the seal area at the glacier bed. The lakeward end of the ice dam probably becomes an ice shelf, but that is not fundamentally important to the seal area, the eastern limit of which moves farther westward.

The maximum calculated values of basal H_t along the trend of low head at the glacier bed—the seal area—occur near point E. This last remaining point of seal becomes buoyant and decouples from the bed when the lake rises to level L_3. Despite the upward slope of the glacier bed between points F and O, values of H_t steadily decline (surface STUVO) all the way from the seal area (E) to the ice terminus at Rathdrum valley (point O). Thus, when the seal at E has become buoyant, there is no further head barrier to resist drainage from the lake.

The seal of the Lake Missoula ice dam is actually somewhat complicated, for it occupies a 4-km segment of the bed (Fig. 19A). That whole segment becomes unstable only when the lake surface rises to the altitude 1,275–1,280 m, approximately the maximum lake level known from ice-rafted erratics. A cross section through the seal area shows that H_t is well above the 1,280-m maximum lake level, except near the deepest point of the ice dam against the steep north face of the Bitterroot Range (Fig. 19B). The stable form of underflow through the seal probably is a single tunnel; to form a basal sheet, the water would have to spread out in spite of the lateral gradients of potential H_t that tend to confine it (compare Nye, 1976, Appendix C).

Along a section across the steep-sided southern part of the trough, the lateral directions of H_t are nearly level despite steep glacier-bed slopes (Fig. 19C). A single tunnel in the seal area may have divided downglacier into several tunnels that together conveyed the water to the ice terminus. The downglacier-shoaling Pend Oreille trough divides into two arms toward the former ice terminus (Waitt, 1984, Fig. 2). Field evidence does not suggest a point from which water issued from the ice margin; rather, it suggests that the great floods fanned across the upper Rathdrum valley from the entire ice margin. This behavior would be similar to jökulhlaups from Grímsvötn, which, at the ice margin, issue simultaneously from three or more separate conduits that must be connected upglacier (Björnsson, 1974).

A Missoula jökulhlaup probably waxed to full flood within hours. Even in small ice-locked lakes, water is slightly warmer than 0 °C; Lake Missoula, with its broad, nonglaciated southern margin (Fig. 1), may have been several degrees warmer. During flow beneath the ice, potential energy lost by the lake water is converted mainly to heat, which may dominate effects of initial temperature of water (Nye, 1976). Heat is transferred efficiently from the flowing water to the tunnel walls, where the ice is almost certainly at its pressure-melting temperature. After flow begins, the subglacial tunnels thus enlarge exponentially (Björnsson, 1974; Nye, 1976; Clarke, 1982), and water drains at swiftly increasing rates through them.

Jökulhlaups from many ice-dammed lakes end only when the supply of lake water is exhausted (Post and Mayo, 1971; Clarke, 1982). A jökulhlaup from Grímsvötn, Iceland, however, ends when the pressure of overburden ice squeezes the tunnels shut before the supply of lake water is exhausted (Nye, 1976, Fig. 10). Thus not all of the water of Lake Missoula necessarily escaped during a typical jökulhlaup, the outlet of which was 120 m above the bottom of the lake at the ice dam (Fig. 19A). Preliminary calculations, however, suggest that the tunnel diameter became greater than the ice dam was thick and therefore that during a typical jökulhlaup the tunnel roof collapsed and allowed most of glacial Lake Missoula to escape. A definitive answer can be given only by detailed analyses of the dynamics of flow of ice and water within the ice dam.

During deglaciation, the thinning ice dam became hydraulically unstable at progressively shallower lake levels. The last many floods were therefore of much less volume than would have escaped from the maximal 2,500-km^3 lake. The flood-laid rhythmites and the Lake Missoula rhythmites are regionally thinner and finer upsection (Figs. 4–8 and 15)—evidence that later floods were indeed smaller (and therefore more frequent) than were earlier ones. The number of varves in the upper 15 or so Lake Missoula bottom-sediment cycles is much less than the average for all lake cycles (Chambers, 1971, Appendix III)—separate evidence that toward the end of its existence the lake dumped with increased frequency. Even half the maximum lake volume (1,250 km^3) sufficed for a mighty

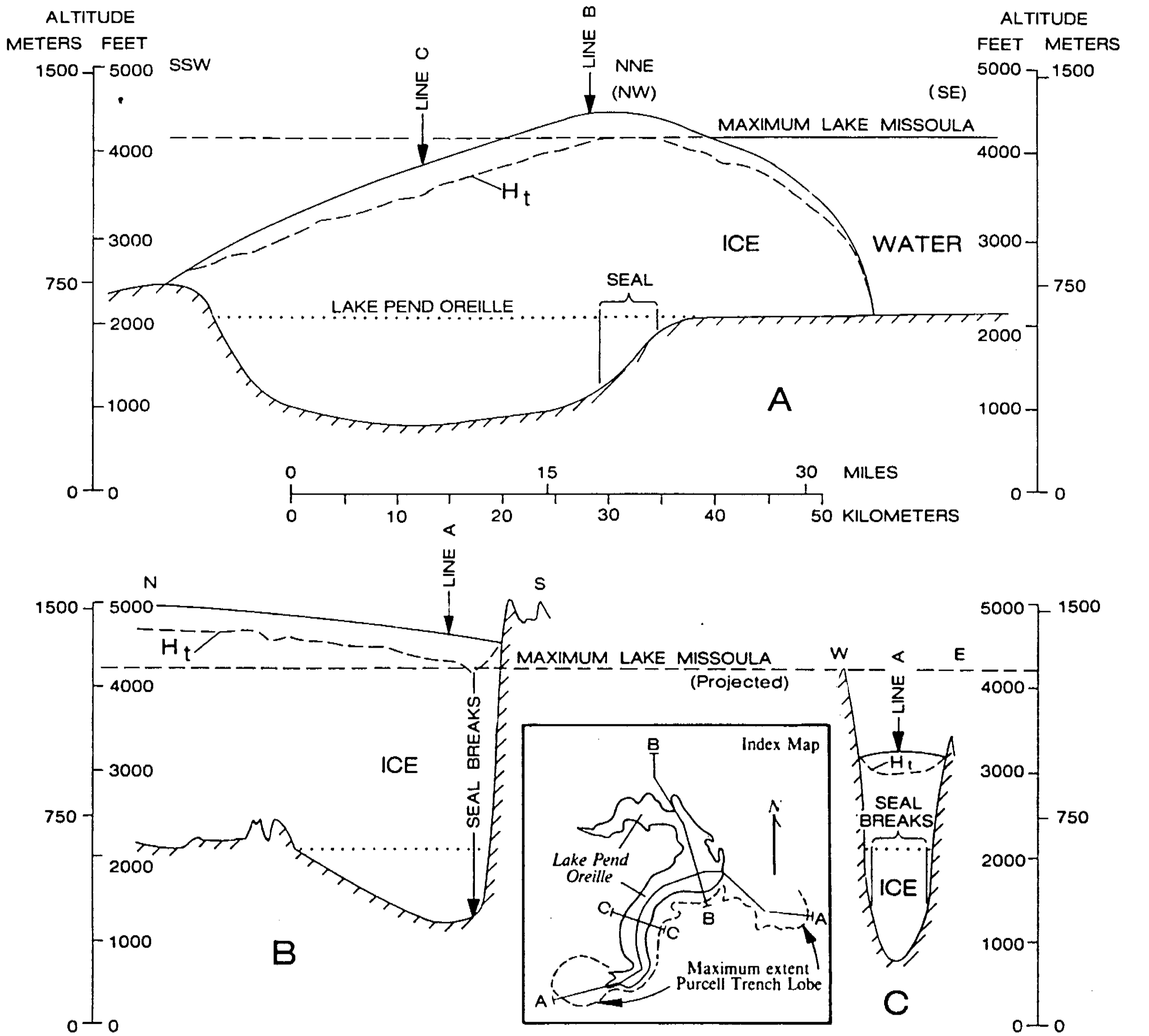


Figure 19. Sections through ice dam. The all-important ice-surface profile is only crudely known by sparse reconnaissance. (A) Longitudinal section; (B) cross section through seal area; (C) cross section through deepest part of Lake Pend Oreille.

flood down the Columbia River valley and probably also across the Channeled Scabland.

The swift and repeated dumping of glacial Lake Missoula is thus explained by an ordinary hydraulic mechanism. The explanation is devoid of various improbable causes that have been suggested over the years: subglacial volcanic eruptions, extreme rates of surface melting, collapse of the ice dam by the weight of water behind it, weakening of the ice dam by ice stagnation, shuffling advances and retreats of the ice margin.

AGE, CORRELATION, AND NUMBER OF FLOODS

Relation to Ice Sheet, Ash Layers, and Radiocarbon Dates

Proof that only one graded backflood rhythmite is produced per Missoula flood permits revisions in the inferred age of the floods. Earlier speculations such as the notion of an "early Pinedale" flood 18,000 to 20,000 yr ago (Richmond and others, 1965; Bretz, 1969; Baker, 1973), are now suspect because of limiting ages on the Cordilleran ice sheet, Lake Missoula, and the Missoula floods. Glacial Lake Missoula could have existed only within the broad limits between preglacial ^{14}C dates as young as ~17,200 yr B.P. and postglacial dates as old as 11,000 yr B.P. in southernmost British Columbia (Clague, 1981, p. 13 and 17). If the Purcell Trench lobe took a millennium to advance 100 km from there to the Bitterroot Range and a millennium to retreat back into British Columbia, then Lake Missoula existed only between about 16,000 and 12,000 yr B.P. The lake probably existed for only about half this period, for the known varves within Lake Missoula bottom sediment or between flood-laid beds in other glacial lakes sum up to <2,500 (Chambers, 1971; Atwater, 1983).

The age of the later Missoula floods into southern Washington is limited by the intercalated 13,000-yr B.P. Mount St. Helens ash (Mullineaux and others, 1978), which overlies at least 28 flood rhythmites and underlies at least 11 (Waitt, 1980b). A new radiocarbon date from a shelly dune at the top of the third Missoula-flood rhythmite below the ash bed at Mabton is 14,060 ± 450 yr B.P. (USGS-684). The 11,250 ± 250-yr Glacier Peak ash-layer G (Mehringer and others, 1984) postdates ice-sheet retreat in Washington and Montana (Waitt and Thorson, 1983); it overlies deposits of one huge flood but not those of small floods that followed deglaciation of the Columbia valley (Waitt, 1982a, 1982b). All considered, the various limits on the ice sheet and floods suggest that glacial Lake Missoula existed for 2,000–2,500 yr between 15,300 and 12,700 yr B.P.

Relation to Bonneville Flood

Near Lewiston, Idaho, the Lake Missoula floods are stratigraphically related to the great Pleistocene flood from Lake Bonneville, Utah. Scott and others (1983, Fig. 5) have established a new radiocarbon chronology for Lake Bonneville. It had been thought that the Bonneville flood occurred ~30,000 yr B.P. and therefore predated the Lake Missoula floods (Malde, 1968; Baker, 1973, 1978a), but the new data show that the lake rose gradually between about 26,000 and 16,000 yr B.P., after which it stabilized at the level of a spillway. Some time between 15,000 and 14,000 yr B.P., perhaps just after ~14,300 yr B.P. (Currey and others, 1983), the alluvial spillway failed by catastrophic headcutting and abruptly drew the lake down 115 m. Along the Snake River Plain, this flood created scabland, boulder fields, bars built up into tributaries, and other features similar to those caused by the Missoula floods in the Channeled Scabland (Malde, 1968). The Bonneville flood descended the Snake River canyon to the Columbia, merging its deposits with those of the Missoula floods.

Most flood deposits in the Snake valley below Lewiston were laid by backflood *up* the Snake from the easternmost scabland channel (Bretz and others, 1956). Bretz (1929) inferred that a great gravel bar blocking Tammany Creek, a Snake River tributary just above Lewiston, was also deposited by the Missoula flood(s), but he later suggested that, instead, this deposit might be of the Bonneville flood (Bretz, 1969, p. 531–532). Baker (1978a) agreed, calling it "probable Bonneville flood deposits." At the downriver end of Tammany bar, the deposit of pebble to boulder gravel consists of about half Columbia River Basalt clasts and half diverse crystalline, volcanic, dike, and metamorphic rocks of upper Snake River provenance. The generally openwork gravel shows many tiers of long-sweeping foreset beds, each several metres thick, dipping down the Snake valley (Fig. 15). At the Clearwater confluence at Lewiston, a 12-m exposure of this gravel has tall foresets dipping down the Snake and *up* the Clearwater (Waitt, 1983). The flow down the capacious Snake valley was therefore voluminous enough to backflood bedload cobble gravel tens of metres deep up a tributary valley that is 2 km broad; it could have been no other than the great Bonneville flood, perhaps half the volume of a large Missoula flood. Abruptly overlying the Bonneville-flood gravel at Tammany bar, there is an apparently completely exposed sequence of 21 finer graded beds (discussed above), deposits of successive Missoula backfloods (Figs. 15 and 16).

Number and Periodicity of Missoula Jökulhlaups

From stratigraphic successions of ~40 rhythmic beds at exposures in Montana, Washington, and Oregon, Waitt (1980b) inferred that ~40 great jökulhlaups had escaped last-glacial Lake Missoula. Only one of these sections has both base and top exposed. There may be unexposed beds beneath the other sections; still other sections are too high and distant from the main floodways to have received sediment from small floods. The number "40" is a minimum; there were at least that many huge floods during the last glaciation.

More than 50 beds are exposed near Cummings Bridge in the Walla Walla valley (Fig. 1); Bjornstad (1980) counted 62 beds at Touchet. Atwater (1983, 1984) counted 80 or more beds, each of which he inferred as having been laid by a separate Missoula flood into glacial Lake Columbia. Although problems remain on the number and correlation of events attributed in various areas to successive Missoula floods, regionally scattered sections indicate that there were >40 colossal last-glacial floods, probably >60.

The typical upsection thinning and fining of rhythmites throughout the region indicates that the later Missoula floods became generally smaller. The trend is logical; as the controlling Purcell Trench ice dam became thinner during deglaciation, the seal should have detached from the glacier bed at progressively lower lake levels, and the later floods have become generally smaller and more frequent. In the lower Yakima valley, eleven rhythmites overlie the ash couplet at the relatively downvalley and low-altitude (185 m) Mabton section, but only five overlie the ash farther upvalley at Zillah (245 m), and only four overlie it at Buena (255 m). In the Walla Walla valley, 11 flood-laid beds overlie the ash couplet at the Burlingame canyon section (150 m); the lower and more downvalley Cummings Bridge section (120 m) exposes at least 50 beds, 18 of them above the ash couplet (Fig. 1) (Bjornstad, 1980, Fig. 32). Some of the late floods into both valleys clearly were too small to leave a record at higher altitude and more distant sections.

The radiocarbon date of ~14,060 yr B.P. from three rhythmites below the 13,000–yr B.P. Mount St. Helens set-S ash suggests a period 365 to 135 yr between those 3 floods. That range, however, is inconsistent with other data that indicate a period much less than 100 yr. Waitt (1980b, p. 675) suggested that the period between successive Missoula jökulhlaups was between 80 and 320 yr, but probably "100 yr or less." The new data and analysis herein refine the range.

Of the 40 to 80 graded flood-laid beds in some valleys (for example, Figs. 4 and 7), only 21 beds overlie the Bonneville-flood gravel atop Tammany bar at Lewiston, which suggests that at least 10–20 Missoula backfloods predated the Bonneville flood. The 13,000–yr B.P. Mount St. Helens set-S ash is overlain by 11 flood-laid rhythmites at low-altitude (185 m) sections (Figs. 4 and 5) but by fewer at higher sections (Fig. 6). Several of these smaller, late floods cannot be represented at the high-level (260 m) and distant Tammany bar section. If all 11 post-ash floods missed Tammany bar, then the 21 beds there were deposited between 14,300 yr B.P. (maximum age of Bonneville flood) and 13,000 yr B.P. (set-S ash): the mean period between those Missoula floods was <60 yr. This range is compatible with the period of 35–65 yr suggested by the inferred water budget for Lake Missoula and of 20–60 yr more accurately given by interflood varves. The average period between floods indicated by varves is about 30–40 yr. At the glacial maximum, it was longer; during deglaciation it was shorter.

REPLY TO CRITICS

From mainly geomorphic studies, Waitt (1977), Baker (1978a), and Mullineaux and others (1978) inferred that field evidence required no more than two late Wisconsin Missoula floods—one before 14,000 yr B.P., the other just before 13,000 yr B.P. Soon afterward, however, evidence from rhythmic backflood beds could be explained by no hypothesis other than that of dozens of successive floods (Waitt, 1980b). Critics of dozens of floods doubt this evidence and instead hold that transient hydraulic surging deposited many beds during a Missoula flood.

The many-beds-per-flood hypothesis was suggested by Bretz (1929, 1969), but it was developed mainly by Baker (1973) when it accorded with available field evidence. Bjornstad (1980, 1982) examined exposures in the Walla Walla valley (Fig. 1), including some I had studied, but he inferred that there had been only one or two floods, each depositing numerous graded beds. In Badger Coulee (Fig. 1), Bunker (1982) gave further proof of a subaerial episode at the ash-couplet horizon but attributed the enclosing slack-water sediment to two floods—one pre-ash, one post-ash—that each deposited numerous beds. Bjornstad's and Bunker's views accord with those of Baker (1973, 1978a), but they sharply discord with the process, chronology, and number of floods inferred here.

Central Washington

1. Patton and others (1979) and Baker (1983) claimed that my evidence of multiple discharge from the "distal" slack-water facies (Waitt, 1980b) has not been found in the coarse "proximal" flood-bedload facies and that my scores-of-floods hypothesis is thus wanting. Such evidence, however, does exist: the lower and middle beds at Mabton and at Touchet *are* coarse (Waitt, 1980, Fig. 6), as are varve-topped flood beds at Rock Island bar and in the lower Latah and Sanpoil valleys (discussed above). The coarse bases of some rhythmites are scoured into or through underlying coarse layers of rhythmic sections; where such coarse bases of successive rhythmites amalgamate, the contact between them becomes invisible—one reason why few bars and other coarse "proximal" deposits in the Channeled Scabland show definite evidence of successive events.

2. The beds in Rock Island bar reveal at least 4 separate floods from glacial Lake Missoula prior to, and during, the circa 14,000-yr B.P. or older maximum stand of the Okanogan lobe of Cordilleran ice; Atwater (1983) showed stratigraphic evidence of at least 13 separate floods into glacial Lake Columbia before and during the maximum stand. All of these floods predate the only discontinuity that Bunker (1982) acknowledged at the 13,000-yr B.P. ash couplet.

Badger Coulee

Bunker's (1982) description of flood sediment in Badger Coulee is compatible with my synthesis of the region, but his regional speculations exceed his data, which are not critical to the scores-of-jökulhlaups hypothesis.

1. Bunker argued that the water-laid character of the silty upper part of beds in Badger Coulee denies the existence of loess between rhythmites at other places. Actually, he described only zones *d* and *e* of rhythmites, which I inferred to be water-laid (Waitt, 1980b, p. 656–658 and Fig. 3). Loess indeed overlies these zones of successive graded rhythmites in many places (Fig. 2).

2. Bunker claimed that my only evidence for a lengthy break at rhythmite tops is loess. This claim ignores the steep-cut channels, shelly dunes, and other presented evidence of successive rhythmites at nearby sections.

3. Except for the ash horizon, Bunker inferred that all other horizons between similar beds represent only hours and were caused by changing intraflood currents. Rather, the discontinuity made conspicuous by the ash couplet is merely less conspicuous at the other similar horizons of the regularly repeating sedimentary motif (see Figs. 4–6). The fine-grained horizon containing the ash couplet atop one rhythmite is identical to horizons atop the other rhythmites in several stratigraphic sections (Figs. 4–6).

Walla Walla Valley

1. From reverse grading at the bases of certain rhythmites, Bjornstad (1980, 1982) inferred that sedimentation was uninterrupted through many or all successive rhythmites. The basal parts of some rhythmites in northern Washington and Idaho are also reversely graded (Waitt, 1984, Figs. 6 and 10), yet varved beds between them unarguably demonstrate long intervals of nonflood. A shell-dune horizon at Mabton, firm evidence of a long break between floods (Waitt, 1980b, Fig. 10), locally overlies a reverse-graded zone. There are at least two causes of such reverse grading: (a) modern jökulhlaups wax to maximum flow not instantly but progressively (Thorarinsson, 1957; Mathews, 1973; Björnsson, 1974; Clarke, 1982); (b) a flood sweeping across dry land or shallow lakes may mix fine erodible sediment there with the coarser, flood-imported material.

2. Bjornstad (1980), noting that massive silt enclosing the Mount St. Helens ash couplet is more poorly sorted than is typical eolian sediment, asserted that my inference that the silt is loess "is negated." The loess contains minor sand derived from the rhythmite bottoms mixed with the major mode of silt derived from rhythmite tops (Fig. 2). The bimodality was caused by mixing of two *locally* derived sediments, a recognized cause of textural bimodality (Folk, 1974, p. 105–107). Sorting is of course poorer than in ideal eolian sand or loess winnowed by long-distance transport.

3. Bjornstad (1980), following Baker (1973), cited load structures at the contact between some rhythmites as evidence of rapid deposition of successive rhythmites, yet this silt becomes plastic if, after drying, it is rewetted. In the lower Columbia River valley near Portland (Fig. 1), hard, dry, Missoula-flood-laid silt in my garden is made scarcely cohesive by rain, snowmelt, thaw, or intentional watering. A great flood just after rain, snowmelt, or thaw that had saturated the surface layer of silt may well have caused loading of the silt in southern Washington. Many flood beds loaded the underlying varved bed in northern Washington and Idaho, sequences clearly demonstrating long breaks between separate floods (Waitt, 1984). Load structures thus are not unique evidence that successive rhythmites accumulated during one flood.

Regional Correlation

Bunker (1982) charged that stratigraphic sections in the flooded region are "unreliable for erecting a detailed flood chronology." Objective time-stratigraphic data do not exist at every exposure of slack-water sediment, but these deposits exist only because of the Missoula floods, on which there is chronologic control. Chronology is composited from dispersed sections because no one area provides data to both count and date all of the floods.

At least 40 major graded beds are exposed at each of four sections widely separated in Oregon, Washington, and Montana, at least one section being completely exposed (Figs. 4, 7, 8, 14). The actual number of major graded rhythmites (and floods) may prove to be 60, 80, or 100 at complete stratigraphic sections, but that is no flaw in the one-rhythmite-per-flood hypothesis as Bjornstad (1980) and Bunker (1982) charged. No reliable dates dispute that the rhythmite sections within the Columbia drainage basin are cognate and between about 15,300 and 12,700 ^{14}C yr old. The correlation of dozens of fillings and drainings of a lake the volume of present Lake Ontario with dozens of colossal floods through Washington and Oregon is logical and grounded in consistent evidence. Bunker neither offers an alternative to this correlation nor explains the striking rhythmicity of Lake Missoula bottom sediment (Fig. 8).

The hypothesis of scores of periodic, colossal jökulhlaups from last-glacial Lake Missoula is based on conclusive field evidence. New evidence fully upholds the many lines of earlier evidence; the hypothesis is made regionally coherent by the regional distribution of the evidence and by deductive logic. The few-flood hypothesis, however, is unsupported: evidence offered in support of few floods applies as well to dozens of floods. Waitt (1980b) contrasted only the opposite hypotheses, 40 floods versus 1, even though most workers have acknowledged more than one late Wisconsin flood. The few-floods and one-flood hypotheses are only variants of each other: demanding multiple graded beds per flood, both fail for similar reasons.

ON UNIFORMITARIAN CATASTROPHES

Geologists found Bretz's hypothesis of catastrophic flooding unpalatable because his evidence was bizarre and unique and thus beyond belief, because until 1930 or even 1942 no known huge source of water had been identified, and because the evidence was distant from routes of collegiate field trips. Nor had a mechanism for swift release of water been explained, and Bretz's relentless pursuit of field evidence did not sway those who legitimately demanded a plausible account of the origin of the water (Gould, 1978). An underlying cause of general disbelief may have been that the hypothesis seemed to flaunt catastrophism. Although Bretz amply and repeatedly emphasized the uniqueness of scabland evidence, the geologic community remained unpersuaded. Only after decades, when further undeniable evidence (for example, giant current dunes) was published and the source of water identified, and after many geologists had seen some of the startling field evidence, did the hypothesis of catastrophe become acceptable—at last, even fashionable (Richmond and others, 1965; Bretz, 1969; Baker, 1978c).

The scores-of-floods hypothesis completes Bretz's imaginative theory. The governing process is plausibly explained as a common glaciolacustrine process: subglacial jökulhlaups. Repeated Missoula jökulhlaups with a few-decades periodicity differ from modern examples mainly in volume and frequency. The Purcell Trench ice dam was thick, and Lake Missoula, large; the floods were colossal and infrequent compared with modern ones, but processes were similar. Six decades since J Harlen Bretz first outraged geologists, the floods have philosophically come full circle: one colossal "Spokane flood" may have been alien to most reason, but successive jökulhlaups of any size are uniformitarian.

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