SEDIMENTARY EVIDENCE FOR MULTIPLE GLACIAL LAKES MISSOULA

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ABSTRACT

Well-developed small-scale cycles, up to several meters thick, characterize the sediments of glacial Lake Missoula. The cycles are divided into a basal layer composed mainly of silt and very fine-grained sand (silt subfacies) grading upward into a well-formed sequence of glaciolacustrine "varves" (laminates silt-clay subfacies). These subfacies succeed one another in a rhythmical pattern, repeating themselves about 40 times. The silt subfacies probably represents deposition from nearly continuous density underflows on the "delta slope" which grade laterally into the proximal laminated silt-clay subfacies. As the lake basin continued to fill, both subfacies onlapped toward the source. Unconformities at the top of 22 rhythmites indicate subaerial exposure of the lake floor; sedimentary evidence includes "weathered" varve zones, small-scale frost wedges and evidence for subaerial channeling of the laminated silt-clay subfacies. The sedimentary record supports the hypothesis of multiple lake drainages, but there is no direct evidence that each drainage was complete or catastropic. The occurrence of giant current ripples in the Camus Prairie basin indicates that at least some of the drainages were joekullhlaups.

INTRODUCTION

While Lake Bonneville lay for many centuries within a broad basin with no outlet until its rising water level topped a divide, the glacial dam impounding Lake Missoula burst, setting in motion one of several catastrophic floods to sweep across southern Washington (Bretz, 1930, 1969; Pardee, 1942; Bretz, Smith and Neff, 1956; Baker, 1973; Wiatt, 1980). The Lake Missoula floods probably involved the largest freshwater discharges documented in the geologic record (Baker, 1973).

In his comprehensive review of the evidence for repeated catastrophic outbursts from glacial Lake Missoula, Bretz (1969) posed several interrelated questions and problems which still lacked an answer. One of the most controversial topics concerns the number of Lake Missoula outbursts. Bretz suggested that the answer to this question may be contained in the back-water deposits of the flooded tributaries (in southern Washington) and in the glacial lake's bottom sediments. He suggested that each Lake Missoula sedimentary sequence should be separated by an unconformity and that bogs and forests would invade the drained lake floor during episodes of glacial retreat. Upon return of lacustrine conditions, the peat bogs and tree stumps would be buried along the unconformity. Bretz also though that leaching and oxidation would be added to the record.

Although the origin of the channeled scablands and its relation to the Lake Missoula floods has been intensely investigated, very little is known about the lacustrine sediments. At the time of Bretz's 1969 review, the only thing known about the lake sediments was that they are varved and contain randomly distributed ice-rafted fragments.

In this paper I propose a conceptual model describing possible depositional mechanisms controlling sedimentation in Lake Missoula. This discussion is based on a detailed study of vertical sedimentary sequences preserved in the floors of various lake-occupied basins. A description and classification of the Lake Missoula sediment types is presented. sented. The sedimentary record supports the hypothesis of multiple lake drainages and the evidence for this conclusion is also presented.

ACKNOWLEDGMENTS

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A BRIEF HISTORICAL REVIEW

Most authors now accept catastrophic flood water hypothesis of Bretz for the origin of the channeled scablands.

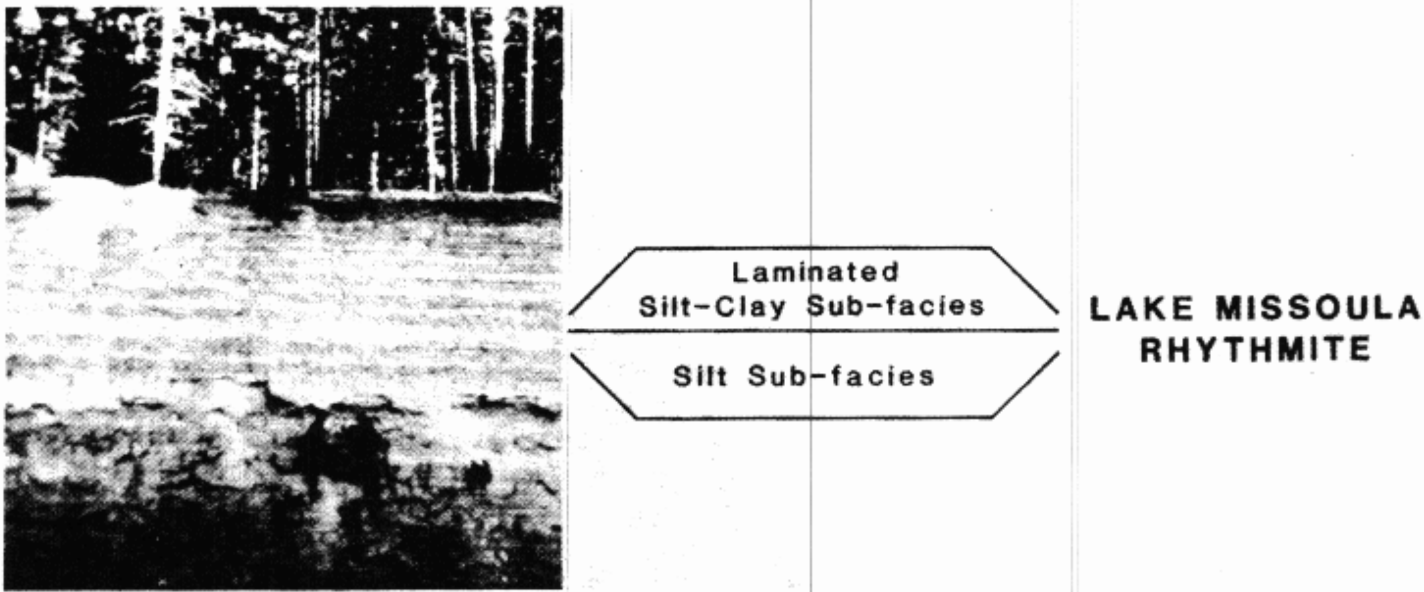

Figure 1. View of the rhythmically bedded Lake Missoula sediment at the "type" locality. The Lake Missoula rhythmite consists of two major subfacies: the silt subfacies (light-toned) and the laminated silt-clay subfacies (dark-toned).

What is still debated is the number of times such an event occurred, with estimates ranging from 2 to 40.

In the course of his studies, Wiatt (1980) reexamined some fo the measured sections of an unpublished study (Chambers, 1971) that described the glacial Lake Missoula bottom sediments. Wiatt (1980) concluded that the Lake Missoula sedimentary record complemented his reinterpreted flood record of the Touchet Beds in southern Washington. The Touchet Beds beds are rhythmic "slackwater" deposits and Wiatt (1980) suggests that each rhythmite represents a separate, discrete flood and that each flooding period was followed by decades of subaerial conditions. Wiatt believes that the Touchet Beds record about 40 Lake Missoula joekullhlaups, or catastrophic outbursts. His interpretation of these deposits differs considerably from the earlier investigation of Baker (1973) who argued that the "slackwater" deposits recorded multiple hydraulic pulses during a single flood. Earlier studies of the flood deposits in eastern Washington led Bretz, Smith and Neff (1956) and Bretz (1969) to propose six, or possibly seven late Wisconsinan floods. Working strictly within the lake basins, Pardee (1910, 1942) suggested one catastrophic draining, followed by a slow draining.

CHARACTERISTICS OF THE LAKE MISSOULA SEDIMENTS

Well-developed small-scale cycles, up to several meters thick, characterize the sediments of glacial Lake Missoula. The rhythmically bedded deposits have a very distinctive sedimentary motif composed of two major subfacies: the basal silt subfacies (light-toned layers; Fig. 1) grading upward into a well formed sequence of glacial lake varves; the laminated silt-clay subfacies (dark-toned layers). A minor subfacies composed of nonlacustrine sediment is the gravel subfacies.

Another sequence of nonlacustrine gravels also occur within the Camus Prairie basin. These gravels form the giant current ripples described by Pardee (1942). Because the origin of these gravels is known, they are identified by a genetic subfacies name; the Flood Gravel Subfacies.

The most complete section of Lake Missoula rhythmites (Fig. 1), located along Interstate 10 at the juncture of the Clark Fork River and Ninemile Creek (Sec. 28, T. 15 N., R. 22 W.) about 35 km west of Missoula, is designated the "type" section. The sedimentary motif described above repeats itself about 40 times at this locality, but because of deep, post Lake Missoula weathering, cycles 33-40 cannot be described in detail. The rhythmites higher in the section are typically thinner (15-33 cm; cycles 26-40) than those lower in the section (50-100 cm). The "type" section is schematically detailed in Figure 2. The location of the "type" section and other localities discussed in the text are shown in Figure 3.

Although widespread, the lacustrine deposits are not coextensive with the maximum area of the lake floor, but are confined to the lowermost parts of the basins, thinning up the valley sides (Pardee, 1942; Alden, 1953). The Lake Missoula rhythmites are generally not preserved in smaller basins proximal to the ice dam. Many conclusions about the lake's history are based on interpretation of the "type" section. Because these deposits are located about 375 m above the base of the ice dam, and much of the glacial Lake Missoula sediments are not exposed, interpretations of the lake's history are temporally and spatially biased.

The terms "rhythmite" and "varve" are not used interchangeably in this report. Glacial Lake Missoula rhythmites are individual units (couplets of the light and dark toned layers described above) with no connotation of time, whereas varves are couplets that may represent annual deposits.

Silt Subfacies

Sediment of this subfacies is dominantly sandy-silt to silty-sand size, with little material larger than medium sand grade (grain sizes estimated in the field by hand lens and Wentworth size standards). Mineral content is dominantly quartz, with micas and dark opaque material associated mainly with the cross-laminated strata.

Several types of primary sedimentary structures have been identified and are described. Most of these structures can be assigned to the facies states B1, B2 and B3 described by Allen

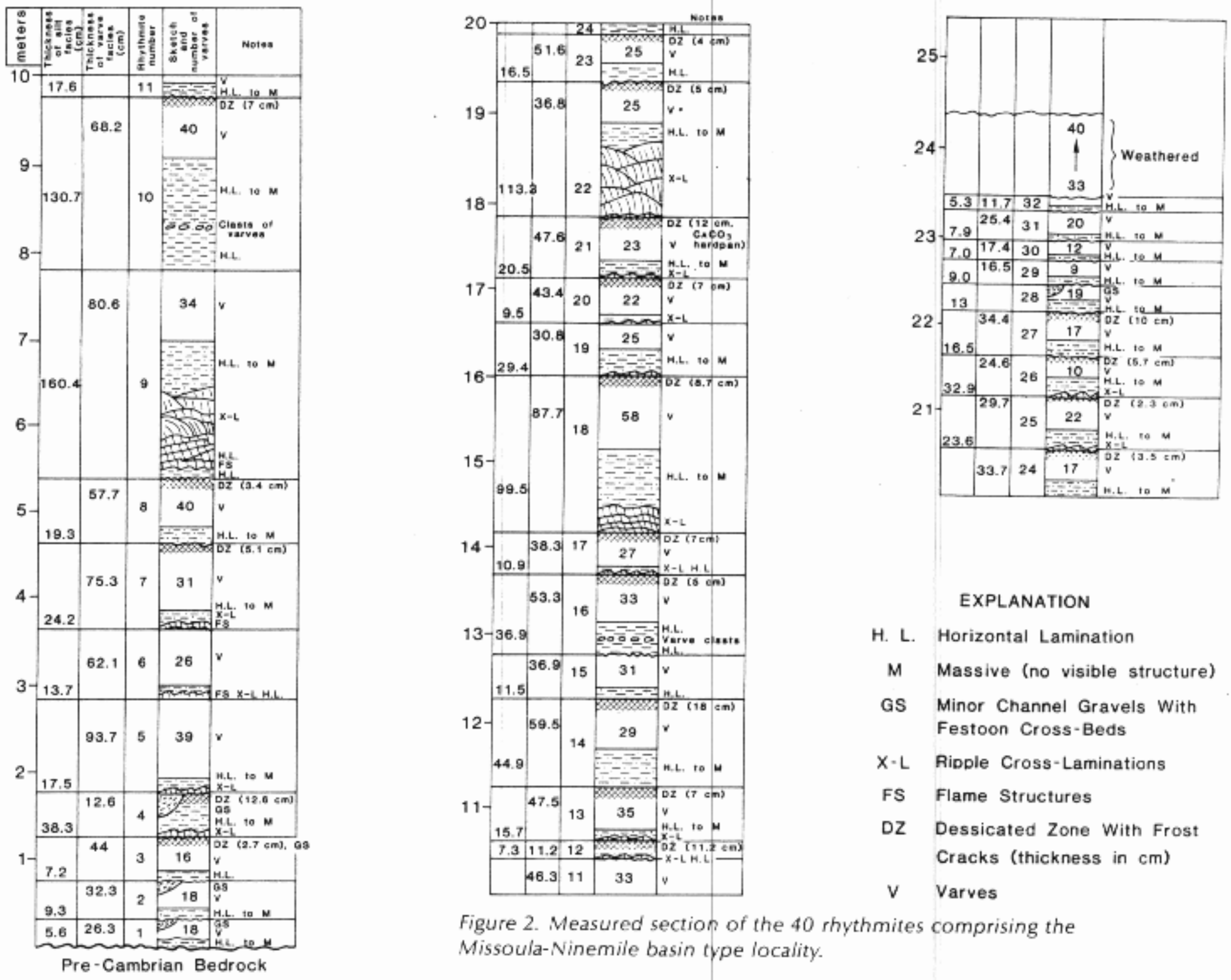

Figure 2. Measured section of the 40 rhythmites comprising the Missoula-Ninemile basin type locality.

(1970) and modified by Shaw (1975). Because sedimentary structures can reflect small changes in the hydrodynamic environment (Jopling and Walker, 1968), it is reasonable to assume that several hydrodynamic states can be preserved within one subfacies, and it is inappropriate to assign each form to a discrete facies, as in the work of Allen and Shaw. Thus, the classification used here is a modified version of the one proposed by Allen (1970) and Shaw (1975). Their State A (Gravel Facies) is here considered to be a minor subfacies not genetically related to the silt subfacies and will be described later. States C, D, E and F are not recognized in the Lake Missoula sediment. The hydrodynamic states recognized in the Lake Missoula silt subfacies are:

1. State B1 - Cross-bedded Sands
2. State B2 - Flat-bedded Silt and Sand
3. State B3 - Cross-laminated Silt and Sand

Cross-bedded Sands (B1)

This state is one of the least common and only trough sets were found (Fig. 4A). These are the coarsest of the sand-sized deposits, generally in the fine to medium size grade.

Flat-bedded Silt and Sand (B2)

The bulk of many silt units are flat-bedded layers composed of coarse silt and fine sand (Figs. 4B, 4F and 6). The abundance of this state appears to be related to the proximity of the sediment source; more abundant in distal sections. The laminations are well defined and occur as thin laminae (« 1 cm) to beds of medium thickness (« 30 cm). Some of the units appear homogeneous and show no well defined internal structure (Fig. 4C).

Cross-laminated Silt and Sand (B3)

Small scale cross-laminations occur in only a few rhythmites at the type locality, but are abundant in sections nearer source areas (eg. the Jocko Valley sections, SW ¼, Sec. 9, T. 17 N., R. 20 W.). Three types of cross-laminations are preserved and classified according to the criteria of Jopling and Walker (1968). Ripple-drift laminations fall into two main categories; in-drift and in-phase forms. In-drift forms (Fig. 4C) are characterized by preservation of only climbing sets of leeside laminae (Type A), or preservation of climbing sets of leeside and stoss-side laminae, with continuity of laminae from one ripple to the next (Type B; Fig. 4D). Ripple laminae inphase (sinusoidal ripple laminations) are characterized by superposition of the laminae and are generally symmetrical in profile with lee and stoss sides of equal thickness (Figs. 4E and 4F).

Soft sediment deformation structures occur sporadically throughout the type section, but are more common at the Jocko Valley sites. Load casts and associated flame structures are the most commonly preserved forms (Fig. 4F). Several varve sequences at the Jocko Valley site show small scale decollement structure which may be attributed to intra-stratal sliding due to overburden pressure, or possibly the grounding of icebergs. The deformed layers are usually bounded by undisturbed varves.

Laminated Silt-Clay Subfacies

The very fine grained bottom sediments of glacial Lake Missoula are varves composed of silt-clay couplets (Sieja, 1959) and are classified into the structural groups defined by Ashley (1975):

Group I

Varves in this group (Fig. 5A) are composed of a thin silt layer and a much thicker clay layer. Ashley (1975) found that these varves consist of a distinct silt and clay layer, and not as graded beds. She did, however, find evidence of grading within the clay layer.

Group II

Varves of this group (Fig. 5B) have a silt and clay layer of similar thickness, but the total varve thickness may vary considerably over the study area. Ashley (1975) states that the contact between the silt and overlying clay is sharp in Lake Hitchcock varves, however the contact is more gradational in Lake Missoula varves.

Group III

These varves form couplets in which the silt is consistently thicker than the clay layer (Fig. 5B). Varves in this group are also considerably thicker than varves in the other two groups. Ashley (1975) found erosional contacts and ripple cross-laminations to be common in Group III varves. She also found that the silt layer can vary considerably in thickness, but the clay layer thickness is relatively constant, and that the contact between the layers is usually sharp. Erosional contacts and cross-laminations are rare to absent in the Lake Missoula varves.

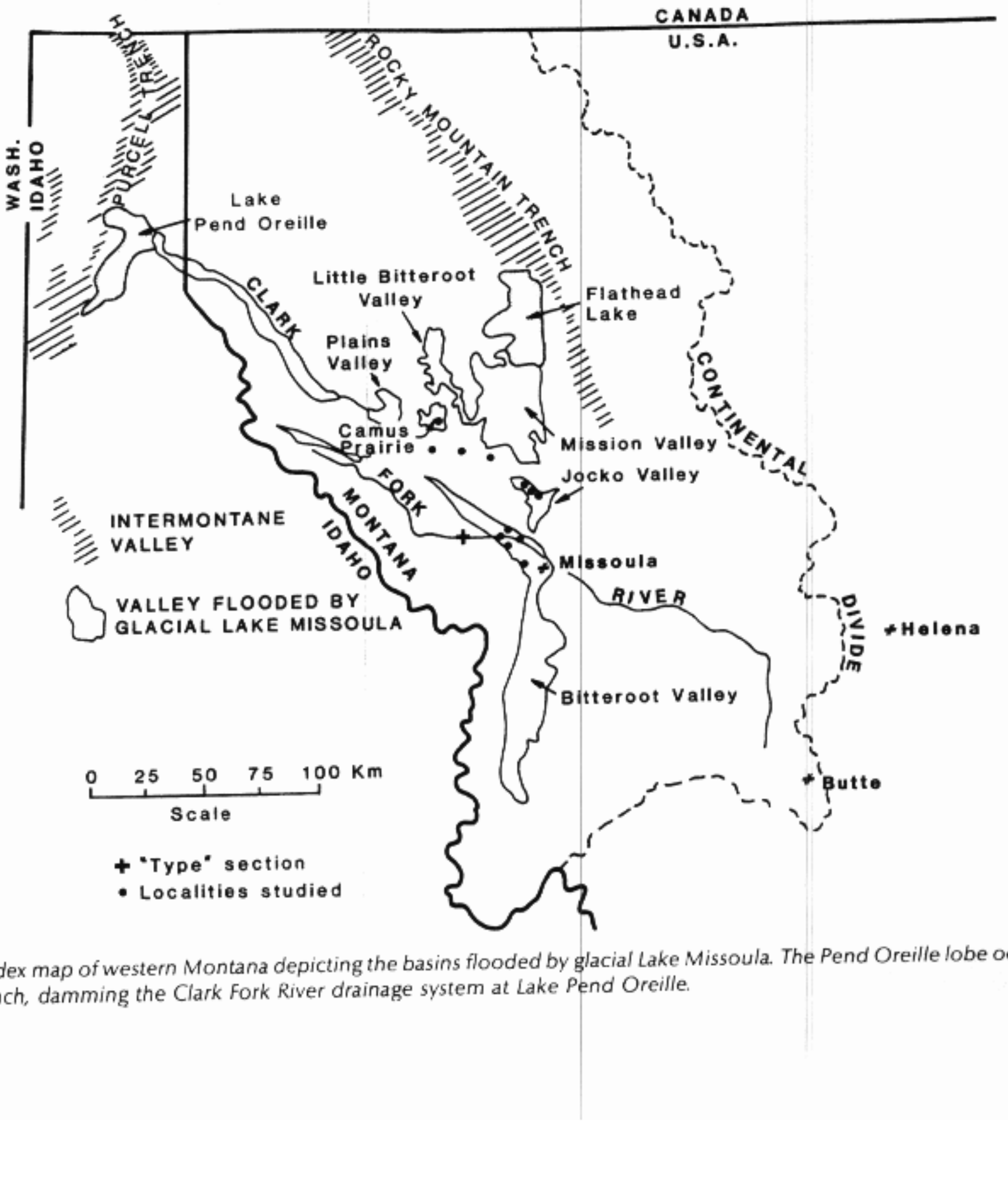

Figure 3. Index map of western Montana depicting the basins flooded by glacial Lake Missoula. The Pend Oreille lobe occupied the Purcell Trench, damming the Clark Fork River drainage system at Lake Pend Oreille.

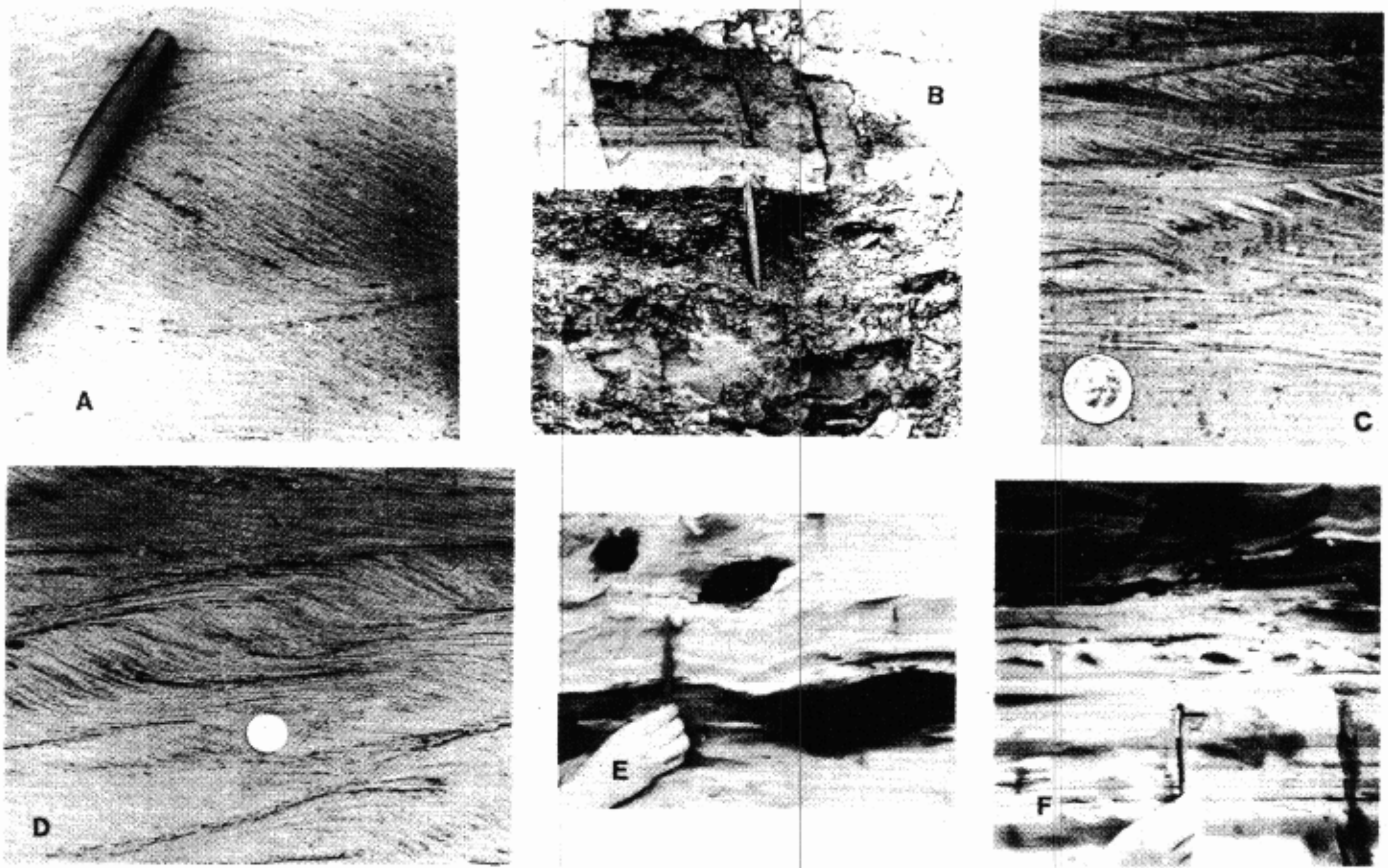

Figure 4. Hydrodynamic states: (A) cross-bedded sand; (B) flat-bedded silt, (above and below pen) and channel fill of the Gravel subfacies; (C) massive and flat-bedded silt overlain by ripple cross-laminated silt; (D) Type B ripple cross-laminations; (E) sinusoidal ripple laminations; (F) from bottom to top, flat-bedded silt, load casts, flame structures, and sinusoidal ripple laminations. The pen is 14 cm in length and a dime is used for a scale in C and D.

Antevs (1951) also described several varve types, two of which are recognized in the Lake Missoula sediments: simple and composite varves (Fig. 5B). Simple varves have distinct light (summer silt) and dark (winter clay) layers, but a very thin silt lamination may occur within the clay layer. Composite varves are characterized by numerous, thin clay laminae within the summer silt layer, producing subordinate couplets resembling thin, or faint, true varve. Ashley (1975) also described similar types of varves within her major Groups.

Gravel Subfacies (A)

Sediment within the pebble-to-gravel grades occurs locally between rhythmites and is considered to be a minor component within the lake deposits. Pebble imbrication is apparent in several exposures. These deposits have a characteristic channel-shaped geometry with a flat top and overlie a scoured surface (Figs. 6 and 4B).

Flood Gravel Subfacies

This subfacies is composed of flood-deposited gravels described by Pardee (1942) and is of similar internal structure and origin as the features described by Baker (1973). The sediment consists dominantly of pebble to cobble size material. Pardee (1942) described the forms composed of this sediment as giant current ripples. Baker (1973) measured the wave-lengths and amplitudes of 60 wave trains of giant current ripples in eastern Washington. Mean amplitudes vary from 0.5 to 6.7 meters, with wavelengths varying from 18 to 130 meters. Some of the wave-lengths I measured are about 100 meters with amplitudes up 5 meters. The giant current ripples exposed in Camus Prairie basin gravel pits exhibit crude, large scale cross-bedding. The ripple troughs are filled with several thin Lake Missoula rhythmites, but they are too weathered to detail internal structure (Fig. 7).

Fragments of a caliche-like soil were found within this subfacies. The fabric, known as K-fabric, has widely varied macroscopic forms, such as massive, blocky, platy or laminar. Because these soils also contain 50% or more by volume $CaCO_3$, the soils qualify for the designation K-horizon (Gile, Peterson and Grossman, 1965, 1966). The most common K-horizon soils found in this study are the K1 (massive, pebble-studded subhorizon) and the K2m (indurated laminar subhorizon). K2m subhorizons contain »90% by volume K-fabric.

Boundary Relationships between Subfacies and Rhythmites

Figure 5B illustrates the transitional nature of the contact between the silt and laminated silt-clay subfacies within a single rhythmite. Group III varves (lowermost varves), pass upward into Group II varves, which in turn grade into several more Group III varves. Group I type varves were not deposited during this sequence. In this study, only flat-bedded silt (State B2) was observed to grade upward into Group III varves of the laminated silt-clay subfacies.

Two kinds of contacts occur between successive rhythmites. The most common contact, preserved in 22 of the

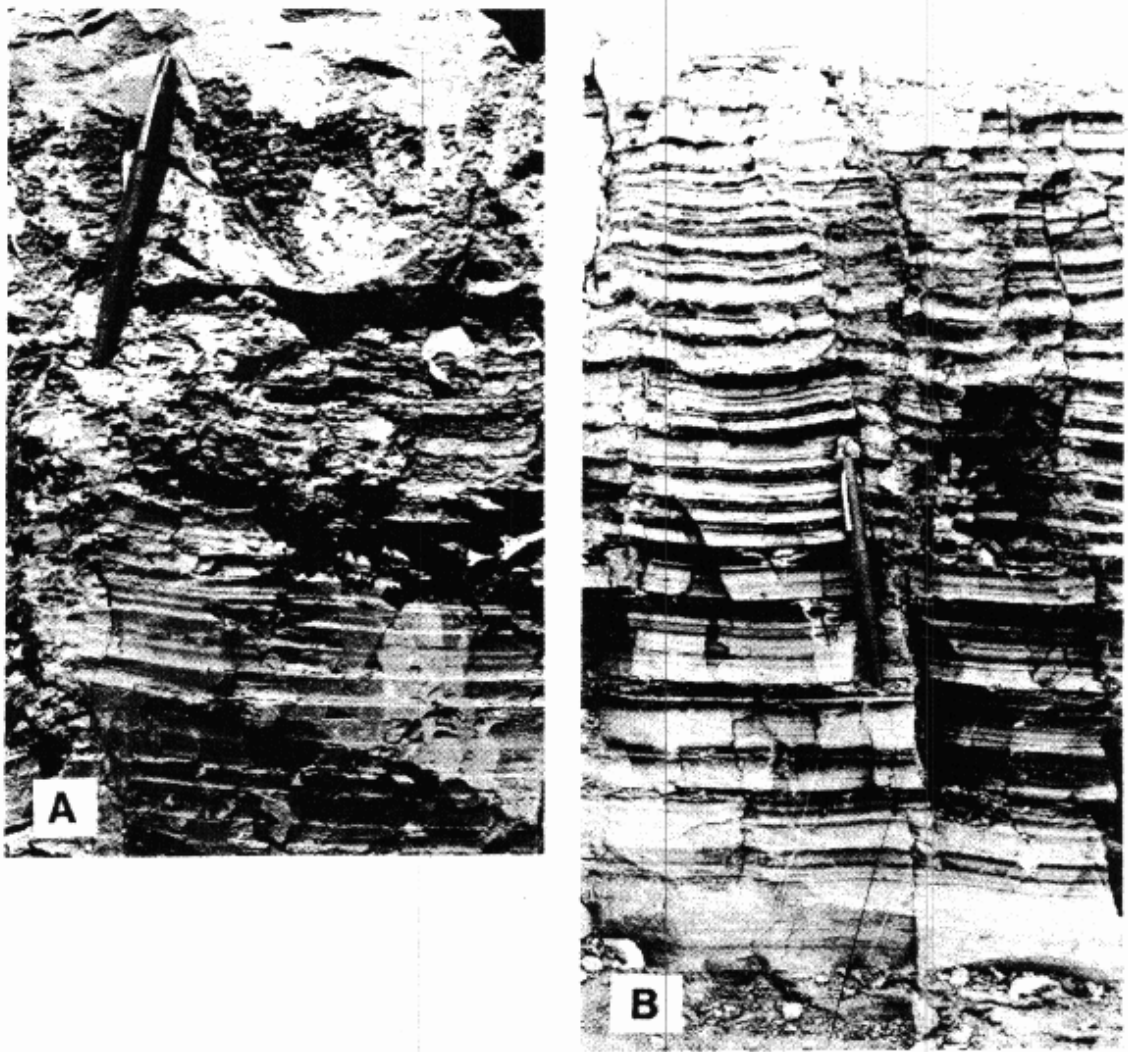

Figure 5. Structural varve groups classified according to the criteria of Ashley (1975). (A) Group I varves; (B) Group II and Group III varves. The simple and composite varve types described by Antevs (1951) can also be observed in this photograph. Pen = 14 cm.

type section rhythmites, is an unconformable surface (Fig. 8A). The contact is characterized by a zone of slightly scoured varves with a dry, crumbly texture, but freshly exposed varves beneath this zone are still moist and pliable. Some of the scouring within this zone probably occurred during deposition of the next rhythmite, as indicated by the presence of varve clasts in the overlying silt layer. These "weathered" zones also appear oxidized and vary from 2-20 cm in thickness. Frost cracks or small scale frost wedges are also preserved within this zone (Fig. 8B); kept open with an infilling of brecciated varves. The other type of contact appears transitional (Fig. 5B), with Group III varves at the top of several sequences, which grade into the basal layer of the succeeding rhythmite.

The tops of several varve sequences are locally channeled and unfilled with sediment of the Gravel subfacies. In some sections, channeling eroded through the varves into the basal silt layer. These small channel deposits occur randomly throughout the Lake Missoula sediments. Sediment within these deposits often shows evidence of oxidation.

Sediment Sources

The Blackfoot Valley glacier, whose terminus is located 56 km northeast of Missoula, probably supplied most of the sediment to the Missoula-Ninemile basin. Sediment entered the basin through the Hellgate Canyon, located east of Missoula. Other sources include the Rattlesnake Canyon glacier north of Missoula, with minor contributions from small alpine glaciers emptying into the Bitterroot Valley south of Missoula (Alden, 1953; Sieja, 1959).

Both the Little Bitterroot Valley and the northern portion of the Mission Valley received large quantities of sediment from the Thompson River lobe. The Mission Valley also received sediment from the Flathead lobe and from local alpine glaciers in the Mission Range. Upper Jocko Valley alpine glaciers supplied sediment to the Jocko Valley basin, while the Plains basin was sourced from either or both the Mission Valley and the Missoula-Ninemile basins (Pardee, 1942; Alden, 1953; Richmond, Fryxell, Neff and Weis, 1965).

PROPOSED DEPOSITIONAL MODEL FOR GLACIAL LAKE MISSOULA

General

Distal glacial lake sediments are relatively easy to recognize, but the processes producing the distinctive varved bedding are still not fully understood (Shaw, 1975; Gustavson,

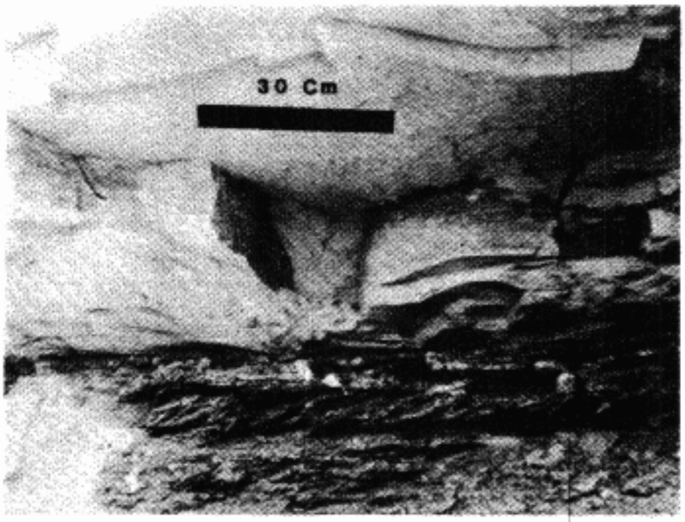

Figure 6. Channel fill deposit of the Gravel subfacies overlain by flat-bedded silt of the next cycle at the Jocko Valley site.

1975; Ashley, 1975). Sediment deposited in positions proximal to the ice-front are transitional between fluvial and lacustrine, consequently it may be difficult to discriminate between these environments on the basis of sedimentary properties (Shaw, 1975). Results of recent studies of contemporary and Pleistocene glaciofluvial and glaciolacustrine depositional systems are used to aid in the interpretation of the Lake Missoula sedimentary sequences (Church and Gilbert, 1975; Shaw, 1975; Gustavson, 1975; Gustavson, Ashley and Boothroyd, 1975; Ashley, 1975).

Hydrological Considerations

Lake Missoula occupied free-draining intermontane basins when a lobe of glacial ice dammed the Clark Fork River at Pend Oreille, Idaho (610 m A.T.; Pardee, 1910, 1942; Bretz, 1969). Besides the Clark Fork, other rivers such as the Bitterroot, Jocko, Flathead and the Blackfoot, which flow into the Clark Fork, were also dammed. Water discharge within this system was probably significantly increased, highly variable and highly seasonal during periods of glaciation.

The Lake Missoula water budget probably fluctuated in response to climatic perturbations that controlled the growth and wastage of the Cordilleran ice sheet. Because of short lived still stands, numerous closely spaced shorelines were etched in the mountainsides. The shorelines may be the aggregate result of several fillings and emptyings of the lake, but did not form in a strictly chronological sequence (Bretz, 1969). Some shorelines on the mountainsides behind the University of Montana campus at Missoula are very distinct, especially if there is a light snow cover (Fig. 9). The most prominent shorelines may reflect longer still stands, or they may have been formed in a short period of time by the action of large wind-generated waves during nearly ice free periods of the Missoula-Ninemile basin. Prominent shorelines rim other basins suggesting that they may have been ice free or nearly so at various times.

At its maximum size, Lake Missoula occupied six major intermontane basins with a water volume of about 2100 cu. km (about half the volume of Lake Michigan) and a maximum depth of about 610-710 meters at the ice dam (Pardee, 1942; Bretz, 1969; Baker, 1973; Richmond, Fryxell, Neff and Weis, 1965). Wiatt (1980) estimated a mean periodicity of 175 years to fill the lake to its maximum volume, which requires doubling the mean annual discharge of 210 cms (7500 cfs). Once the ice-dam formed, the lake probably filled rather quickly.

Recent studies of the thermal structure and suspended sediment concentration and distribution patterns in Lake Malaspina (a proglacial lake in southeastern Alaska) show that sediment enters the lake via underflows, interflows and overflows (Gustavson, 1975). The dominant flow type depends upon the density contrast between the lake and stream water. Heavily silt laden glacial streams would probably enter the lake as a density underflow, depositing the coarser material near the delta margin, and transporting the fines onto the lake floor (Gustavson, 1975; Ashley, 1975). Non-glacially derived stream water does not have much readily available sediment and would enter the lake as an interflow or an overflow (Ashley, 1975).

Early Filling Stage

The Lake Missoula silt subfacies probably represents deposition predominately from density underflows entering the newly created lake. Jopling and Walker (1968) proposed a similar mechanism to explain the formation of a kame delta in a very small Pleistocene glacial lake. Their interpretation is based on a gently shelving lake floor traversed by gentle currents bearing fine sand, silt and clay, filling in the lake.

The classic Gilbert type delta, recognized in modern (eg. Lake Malaspina deltas; Gustavson, 1975) and Pleistocene (eg. Lake Bonneville delta, Gilbert, 1890) lake sequences, forms in a low energy environment with a nearly static water level, where lack of tides, effective waves, or wind-generated currents can redistribute the sediment entering the lake (Gustavson, Ashley and Boothroyd, 1975). The Lake Missoula water level was far from static. Because the water level was rising rapidly in the newly-formed Lake Missoula, the transition between the fluvial and lacustrine environments would be very subtle. Progressive deepening of the lake flooded the larger basins and produced a transgressive sedimentation

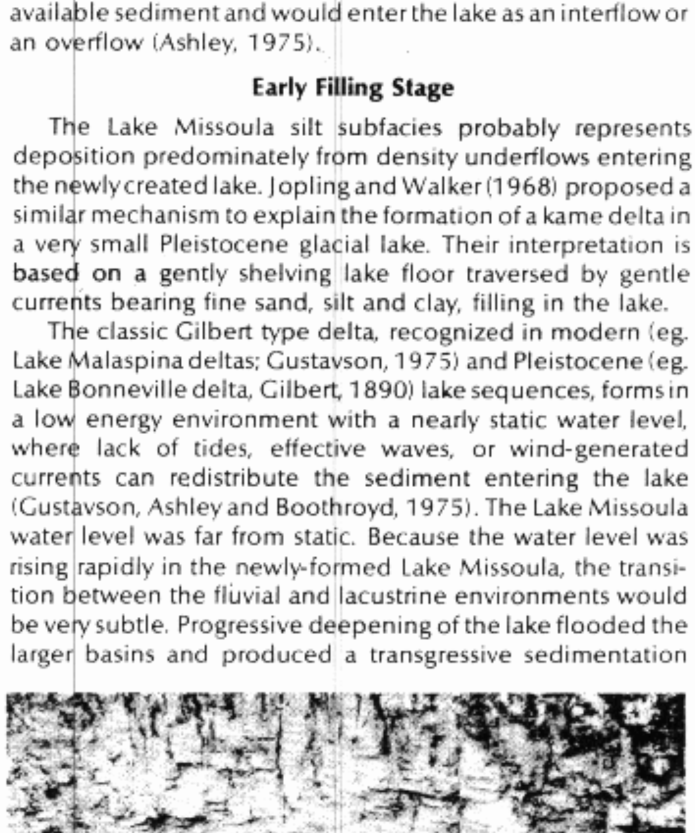

Figure 7. Flood Gravel subfacies (giant current ripples) overlain by a thin sequence of Lake Missoula rhythmites. Fossil grasses(?) were found along the contact indicating a period of subaerial exposure of the basin. The presence of the rhythmites suggests that the last few Lake Missoulas were small and drained with less energy.

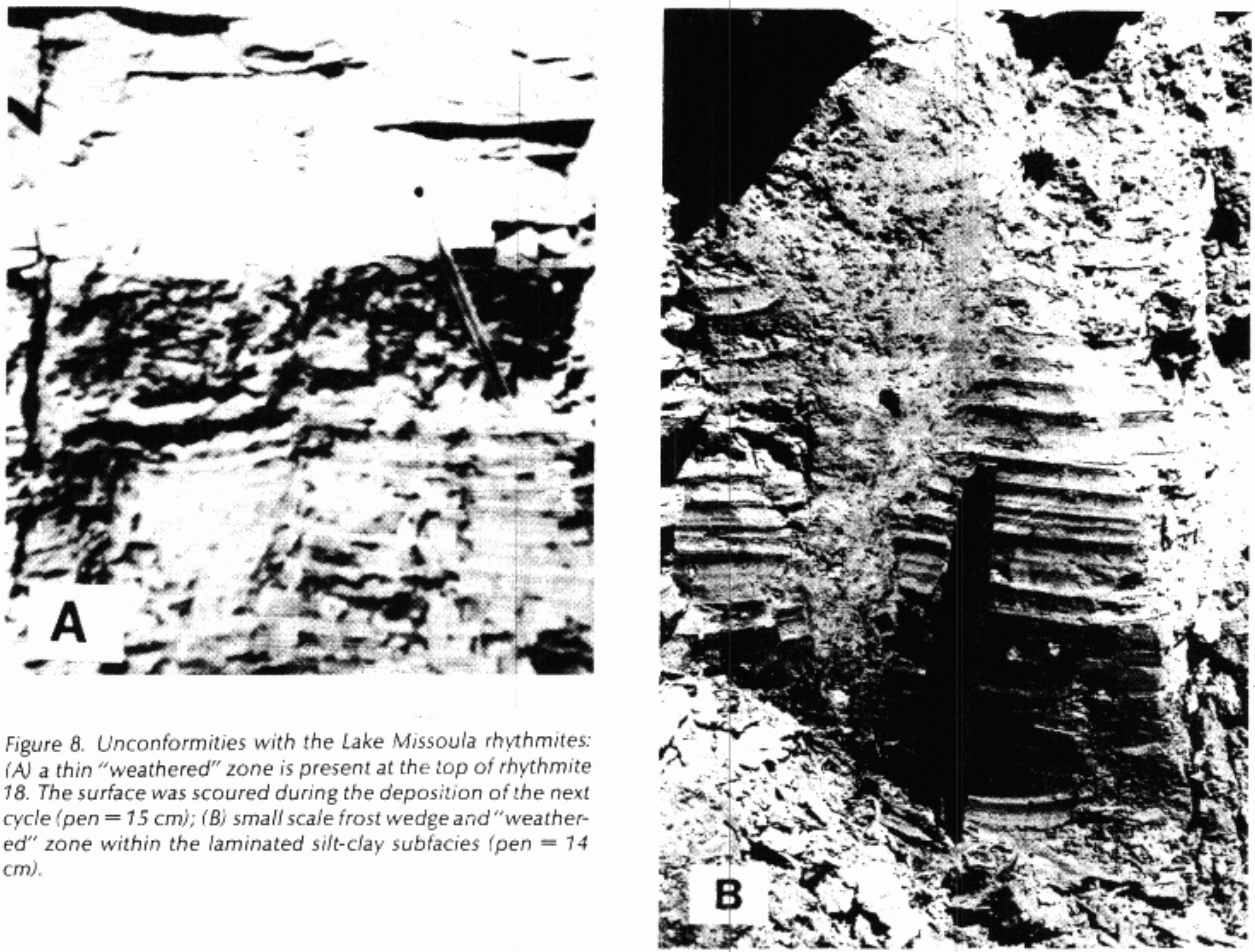

Figure 8. Unconformities with the Lake Missoula rhythmites: (A) a thin "weathered" zone is present at the top of rhythmite 18. The surface was scoured during the deposition of the next cycle (pen = 15 cm); (B) small scale frost wedge and "weathered" zone within the laminated silt-clay subfacies (pen = 14 cm).

pattern. The Lake Missoula "delta" might be considered more similar to the Hjulstroem supra-aquatic type delta, which requires rapid sedimentation in shallow water (Hjulstroem, 1952). In most cases, glaciolacustrine systems are fed by braided streams, but stream channels of other geometries may contribute sediment to the lake basin (Gustavson, Ashley and Bothroyd, 1975). Early in the lake's history, the rivers probably were much like the modern rivers draining western Montana, but, as the basins filled with sediment a more braided pattern developed.

The thin, sheet-like geometry of the silt subfacies is probably the product of coalescing density underflows dispersing sediment over an enlarging lake floor adjacent to an onlapping shoreline. A smooth, gently sloping surface characterizes basin floors infilled by the density underflow transported sediment. This process is now forming a smooth-bottomed floor in Lake Malaspina (Gustavson, 1975).

There is little evidence of internal scouring, graded bedding or intermittent influxes of coarse sediment within the silt subfacies. This suggests that the density underflows entered the lake almost continuously. Because of the more or less continuous rise in water level and sediment reworking near the strand line, cross-laminated sediments were rarely preserved. Once a still-stand was attained, deltas might form in basins proximal to the ice-front. The Jocko Valley section, which contains the thickest rhythmites (very thick silt subfacies) and the most abundant cross-laminated sediment, may be part of a small delta. The sediment was derived locally from the Jocko Valley glacier several kilometers to the east. It is unlikely that deltas would form in basins distal to the ice-front, even during long still-stands.

Later Filling Stage

Recent studies suggest that varved couplets (Laminated silt-clay subfacies) form by two processes (Gustavson, 1975; Gustavson, Ashley and Boothroyd, 1975). The coarser grained silt layer (summer layer) is deposited from density currents and the clay layer (winter layer) is deposited from suspension.

The thickness of the silt layer within the three varve groups appears to be related to the proximity of the source. Group III varves, the most proximal, are interpreted to be the transitional zone between the silt subfacies and the laminated silt-clay subfacies. Group I varves, composed mainly of clay, represent the most distal lacustrine sediment, with Group II varves intermediate to the other groups. Thus, the two major subfacies are time equivalents.

Clay deposition probably occurred year round wherever or whenever water velocity permitted particle settling. Once

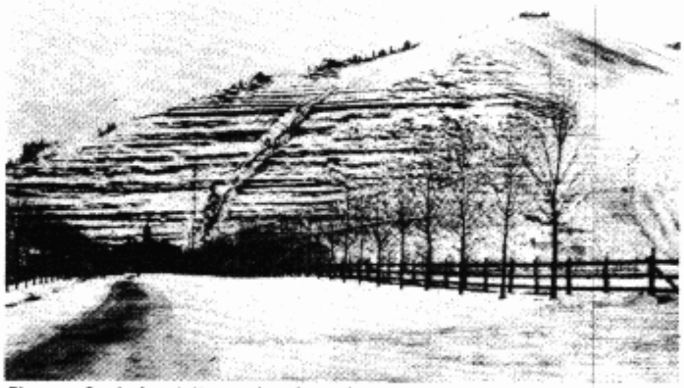

Figure 9. Lake Missoula shorelines on University Mountain behind the University of Montana campus. This photograph was reproduced from the original glass slide taken by J.T. Pardee, which he used in his 1910 publication describing Lake Missoula.

the density underflows ceased (eg. winter) or if the depocenter shifted laterally, the clay-rich "winter" sediment could settle to the lake floor. Gustavson (1975) also suggests that deposition from suspension occurs throughout the year in areas not reached by the density underflows.

Lake Drainages

Marginal-ice dammed lakes, such as Lake Missoula, may drain suddenly when the ice barrier gives way. Mechanisms controlling glacial outbursts, or joekullhlaups, are not clearly understood, but in 1963, all 52 ice-dammed lakes in Alaska and British Columbia drained under or through the ice (Embleton and King, 1968). Subglacial drainage may be initiated by flotation of the ice-dam once a critical water depth is reached; a depth greater than about nine-tenths the height of the ice barrier (Thorarinsson, 1939). Once the ice dam begins to float, water will find its way into crevasses and bedrock. Thermal erosion will enlarge the passages and

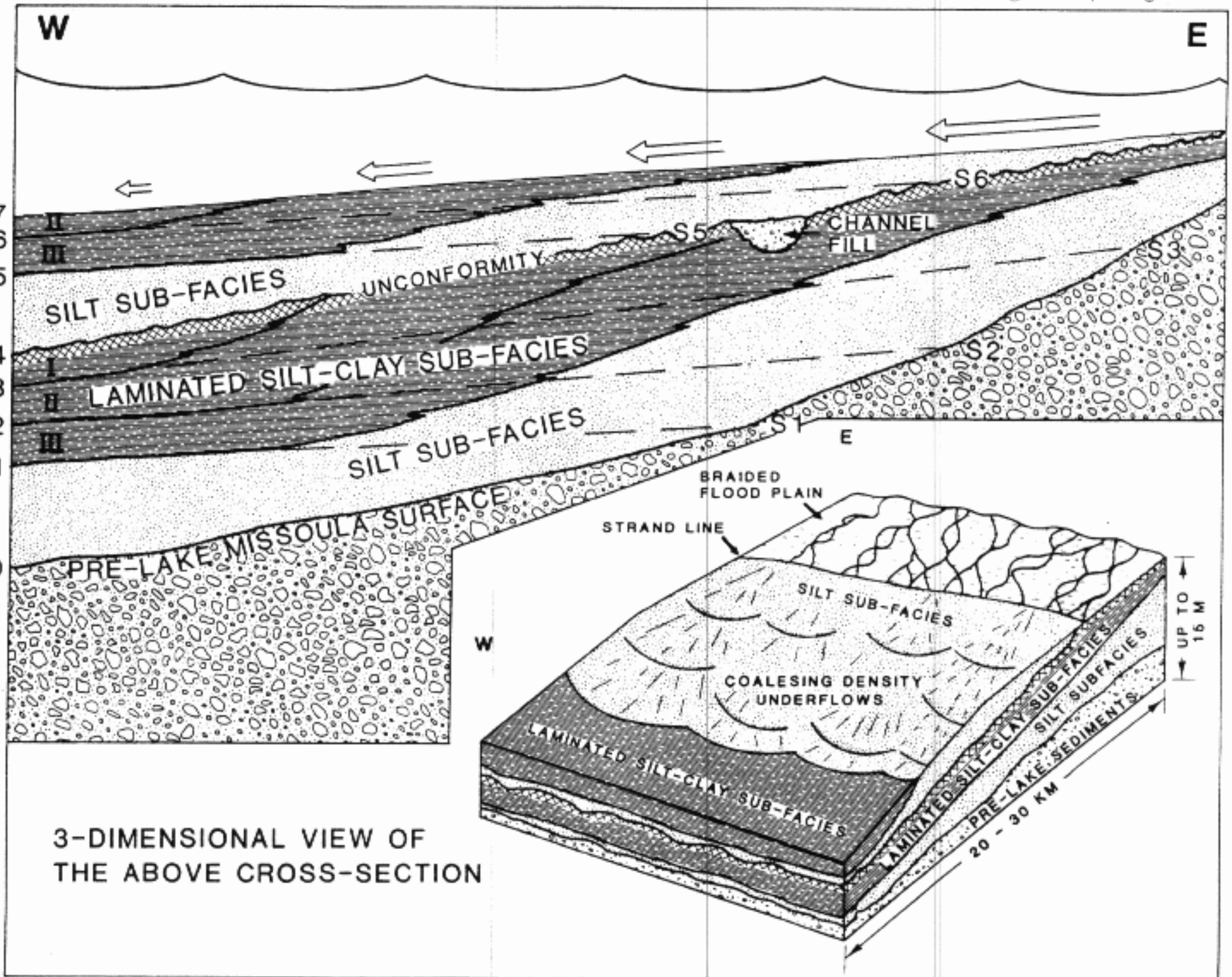

Figure 10. Schematic illustrating the proposed depositional model for the Lake Missoula rhythmites. The insert shows a 3-dimensional view of the cross-section. Note that the vertical scale is in meters and the horizontal scale represents tens of kilometers. Isochrons are indicated on the left (T) and hypothetical strandlines (S) on the right. The transgressive nature of the rhythmites are illustrated in this figure. T4 represents a time of lake drainage and subaerial exposure of the lake floor. Channeling is also indicated. The arrows represent density underflows entering the lake basin, and their length relates to the relative flow rate intensity.

icebergs wedged in the tunnels might help keep the ice mass from falling into its original position once the water level drops (Aitkenhead, 1960). Unless the ice barrier is significantly eroded and broken up, the lake may only partially drain, with no sudden release of water. There is little doubt that Lake Missoula drained catastrophically, the question is, how many times did such an event occur?

Wiatt (1980) believes that Touchet Beds record 40 Lake Missoula joekullhlaups. He also assumed that the 40 Lake Missoula rhythmite sequences described by Chambers (1971) are a record of 40 Lake Missoula floods. Wiatt (1980) slightly misrepresents the conclusions of the study, because Chambers (1971) stated that the Lake Missoula sedimentary record contains evidence for 40 major lake level fluctuations, and that there was no evidence that each drainage was complete or catastrophic. Alt and Chambers (1970) suggested 37 Lake Missoula joekullhlaups. I suggest that the Lake Missoula rhythmite record contains evidence for multiple, major lake level fluctuations, but no evidence that each drainage was catastrophic. I believe that there is some evidence to support only partial lake drainages.

The weathered zones found between the rhythmites are good evidence for subarerial exposure of the lake floor, and indicate that the Missoula-Ninemile basin drained at least 22 times. The maximum water level drop in this basin exceeds 350 m, because the type section is at 985 m A.T. and the highest shoreline is at 1340 m A.T. Rhythmites which appear transitional from one cycle to the next probably indicate only a partial lake drainage. In either case, each rhythmite represents a new Lake Missoula filling sequence, after reconstruction of the ice-dam.

FLOOD EVIDENCE

Pardee (1942) cited the giant current ripples (Flood Gravel subfacies), high eddy deposits and severely scoured bedrock surfaces as evidence for the catastrophic draining of Lake Missoula. The eddy deposits and scoured bedrock occurs within the narrow Clark Fork and Flathead River valleys upstream of the ice-dam. Some giant current ripple trains are found at Rainbow Lake Pass, a saddle connecting the Little Bitterroot Valley to the Plains Valley at 1110 m A.T. Camus Prairie contains the largest volume of the Flood Gravel subfacies and is the only basin which contains this subfacies and Lake Missoula rhythmites (probably distal varves).

Markle Pass and Will's Creek Pass connect Camus Prairie to the Little Bitterroot Valley at 1020 m A.T. and 980 m A.T., respectively. I suggest that the initial water level dropped rapidly in the Plains Valley and Camus Prairie, creating a steep hydraulic gradient between these basins and the Little Bitterroot Valley to the north, and that the giant current ripples formed only when catastrophic flood water spilled into Camus Prairie and the Plains Valley from the Little Bitterroot Valley. Once the water level fell below Rainbow Lake Pass, Camus Prairie received the full force of the flood, which continued until the water level dropped below Will's Creek Pass.

Whenever the Missoula-Ninemile basin contained water, conditions existed for a possible Camus Prairie flood, because Will's Creek Pass is below the elevation of the type section. Floods probably did not occur until a critical hydraulic gradient was set up between the basins. Because of the enormous discharge rates associated with the Lake Missoula floods, it is probable that the last flood destroyed most of the evidence of previous floods. Thus, the occurrence of rhythmites in Camus Prairie indicates that the last few Lake Missoula's were small in volume and drained with less vigor. Wiatt (1980) believes that the thinner Touchet Beds also record smaller Lake Missoula floods.

Pardee (1942) and Baker (1973) suggest that the maximum discharge rates (40 and 63 cubic km per hour, respectively), lasted only a few hours, with waning stages persisting for a week or two. At its maximum, 75% of the lake's volume was stored upstream of Eddy Narrows, a constriction located west of the Plains Valley (Fig. 3). This constriction probably retarded high flow rates after the initial catastrophic breakout of the 500 cubic km of water held downstream (Pardee, 1942; Baker, 1973). Preservation of the rhythmites is evidence of low flow rates out of basins distal to the ice dam.

LAKE CHRONOLOGY

No radiocarbon dates exist for the Lake Missoula rhythmites, mainly because of the pauacity of datable material. About one gram of woody material was collected from a channel deposit of the Gravel subfacies, unfortunately, the sample could not be dated because of in situ contamination. Until datable material is found, only reasonable inferences about the age of the deposits can be made.

The thin weathered zones and the absence of true soil profiles between the rhythmites suggest that the cycles succeeded one another rapidly enough to prevent significant soil development. Wiatt (1980) came to the same conclusion about the Touchet Beds and assigned them a late Wisconsinan age. It is possible that if soils formed, they were eroded during deposition of the next cycle. However, every soil horizon probably would not have been completely removed.

Varves have been used as a chronological and correlative tool (e.g. DeGeer, 1912), but because of widely spaced outcrops, correlation of Lake Missoula rhythmites has been very difficult. Varve couplets were only successfully correlated over a distance of about 25 meters. If correlations were reliable and Lake Missoula varves represent annual deposits, minimum time boundaries could be placed on the rhythmites. We do not know how long it took to deposit the silt subfacies portion of the rhythmite, and we also do not know how many varves were eroded or the duration of subaerial exposure. The age estimates are temporally biased and would only be good for lake levels exceeding 985 m A.T. There are 729 unweathered varves in 31 rhythmites at the typesection, ranging from 9 to 58, with an average of 24 varves per cycle.

A very high concentration of $CaCO_3$ was measured in the weathered zone of rhythmite 21 (Fig. 2). The sediment is about 75% by weight carbonate, which is about an order of magnitude greater than the carbonate content measured in the other weathered zones. This zone qualifies as a K2m subhorizon (Gile, Peterson and Grossman, 1965, 1966). This soil is morphologically similar to the K2m soil fragment found in the Flood Gravel sub-facies at Camus Prairie. It has been suggested that soils of this type require about 10,000 years to form (Ruhe, 1967; Gile, Peterson and Grossman, 1966).

Richmond, Fryxell, Neff and Weis (1965) correlated Rocky Mountain glacial events to Cordilleran events. If their chronology is valid, the K-soils may have formed during the Bull Lake-Pinedale (Wisconsinan) intraglaciation (the period approximately 32,000 to 25,000 B.P.). Curry (pers. comm., 1970) believes that Richmond, Fryxell, Neff and Weis (1965) under-estimated the duration of this intraglacial by about 11,000 years. There appears to be ample time for K-soils to form during the Bull Lake-Pinedale intraglacial stade, thus, the age of the lake sediments may span these glacial stades. Other possibilities include the non-glacial period between the late and early Bull Lake glacial stades, or, the even older Sangamon equivalent interglaciation.

Baker (1973) suggests that the Columbia Plateau contains evidence for flooding in pre-Bull Lake, Bull Lake and Pinedale time. He also states that the early Pinedale flood was the most extensive and probably occurred about 22,000 years B.P. Richmond, Fryxell, Neff and Weis (1965) place the earliest lake as a late Illinoian age equivalent (their Sacagawea Ridge glaciation), and the most recent flood as early Pinedale, with waning lake stages but no flooding as middle Pinedale.

CONCLUSIONS

A conceptual depositional model for glacial Lake Missoula is illustrated schematically in Figure 10. I suggest that the following events are recorded in each rhythmite:

1) shallow water density current deposition of the silt subfacies adjacent to an onlapping strand;
2) progressive deepening of the lake basin and deposition of the laminated silt-clay subfacies;
3) a major drop in water level or complete drainage of the lake prior to deposition of the next rhythmite.

This sedimentary sequence is repeated at least 40 times in a section located 375 meters above the base of the ice-dam. There is little sedimentary record of lower lake stands, because the sediment was deposited primarily within narrow basins which served as flood outlets.

The Lake Missoula rhythmites contain ample evidence for major lake level fluctuations. The thin weathered zones and Gravel subfacies are evidence for subaerial exposure of the lake floor. The Flood Gravel subfacies in Camus Prairie indicates that at least some of the Lake Missoula drainages were joekullhlaups.

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