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SEDIMENTATION IN GLACIAL LAKE MISSOULA

by

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Sedimentation in Glacial Lake Missoula.

by

Richard L. Chambers

The lake bottom sediments are divided into stratigraphic units. Each unit consists of a basal layer of unvarved silt and fine sand topped by a sequence of varved silt and clay. Many different types of sedimentary structures were recognized in the unvarved silt layers. Only lee side laminae were preserved in some ripples and dunes, while both lee side and stoss side laminae were preserved in others. Other ripples consist of a series of sine-wave laminae. The factor controlling the different types of ripples and dunes is due to the traction-load/suspended-load ratio. Other types of sedimentary structures include: wave ripples, planar beds, anti-dunes, curl flow and flame structures. Planar beds are the most common type of sedimentary structure.

Several types of varves were recognized and classified, with modifications and additions, following the nomenclature of Antevs (1951). The different types reflect variations in the thermal stratification of the lake water, rate and influx of sediment, and periodic freezing and thawing of the lake water. The upper portion of 21 varve sequences appear to indicate subaerial exposure of the sediments during times in which the Lake was partially drained.

Each stratigraphic unit is interpreted to represent a partial filling of the lake basin after a drop in water level. The silt layers were deposited as shallow water density underflows forming a gently sloping delta. With rising lake water, the delta retrograded eastward. The varves reflect deposition of glacial rock flour on the lake bottom.

Two flood gravel sequences, separated by a torn apart soil, were recognized at Camas Prairie. The lower sequence was deposited by catastrophic flood waters during late Bull Lake time, followed by another flood during early Pinedale. The soil probably formed during the Bull Lake-Pinedale interstadial. It is possible, however, that the soil formed during the Illinoian-Wisconsin Sangamon interglacial, which would make the soil much older. Without radiometric dates on the soil, any interpretations as to their age is purely speculative.

ACKNOWLEDGMENTS

I would like to thank fellow student and good friend John R. Horner who spent many days in the field with me.

Photo credits are due to Mr. Carl C. Hansen.

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CHAPTER 1.

INTRODUCTION

Glacial Lake Missoula was named and first described by Pardee (1910) and later related to the Spokane Flood and formation of the Channeled Scablands, of eastern Washington, by Bretz (1930), Bretz, et.al. (1956), and Pardee (1942). Most students have concerned themselves with the flood deposits of Lake Missoula, but have made no investigation of the lake bottom sediments. A number of important questions have remained unanswered, among them the question of how many times the Spokane Flood may have been repeated.

The objective of this paper is fourfold: 1) to determine the number of times Lake Missoula drained and filled; 2) to determine the number of years between each drain and fill; 3) to interpret the sedimentation in the lake; and 4) to construct a chronologic sequence of events in Lake Missoula. This paper is an attempt to provide a partial answer to these questions through information gained during a study of the lake bottom sediments and flood deposits.

Previous Work

As early as 1885, T.C. Chamberlain described the terraces on the sides of the valleys in the Flathead Lake region as "a series of parallel watermarks..." He conceived the idea of a glacial ice dam and tentatively suggested that it was located near Pend Oreille and drained by way of Spokane. Pardee (1910) showed that in comparatively recent times an ice dammed lake filled a large part of the Clark Fork River drainage in northwestern Montana (fig. 1). He cited the series of parallel strandlines on the sides of Mt. Jumbo and University Mountain in the Missoula Valley as evidence for the existence of the former lake.

In 1923, Bretz studied the origin of the Grand Coulee in the Washington portion of the Columbia Plateau. At that time, however, he had not yet conceived the idea of flood origin nor the scabland complex. It was not until 1925 that Bretz used the term "Spokane Flood" to refer to the origin of the Grand Coulee, but suggested no source for the water. By 1930, Bretz was convinced that the "Channeled Scablands" were the result of catastrophic flood waters from Lake Missoula. The topographic setting of the lake's ice dam, altitude of the lake surface, and water volume contained all the necessary elements for a catastrophic draining when that ice dam burst.

A more conservative view for the origin of the "Scabland" tract is held by R.F. Flint (1938). He argued that glacial stream water never attained any great volume at any time or place, and insists that the water discharge was even less than that of the Snake River of today. Flint theorized that the scablands were made by streams during the removal of valley fill. Many of Flint's interpretations are not

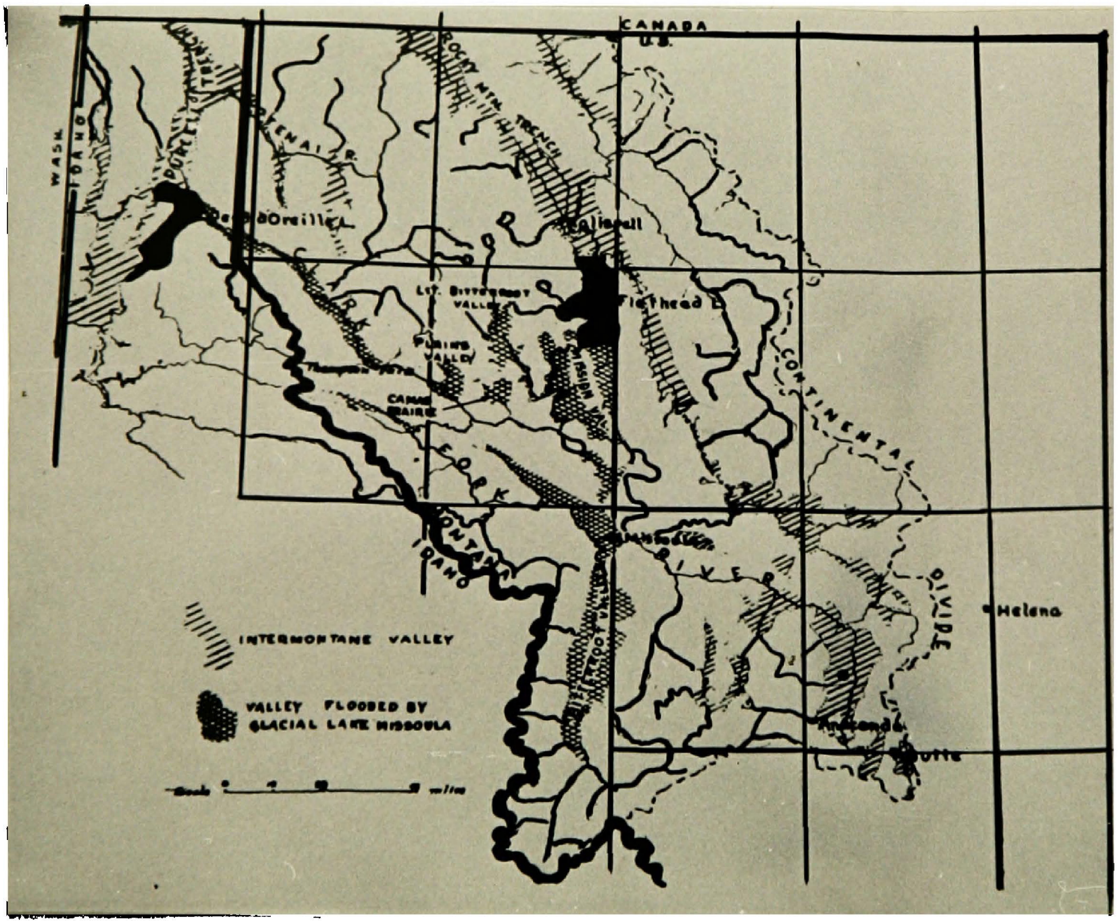


Fig. 1. Index map for Glacial Lake Missoula.

borne out by the constructional forms and stratification in the scablands, and his hypothesis of a "normal discharge" does not seem to be a reasonable solution for the observed landforms (Bretz, et.al., 1956).

According to Bretz (1969) some of the flood water went down the Snake River. At its northern end, giant current ripples lie on flat hill tops 500 feet above the present river level. Many of the rounded Snake River cobbles and pebbles in this deposit show percussion flaking and fracturing. Angular faces and edges on both cobbles and fine material have been superimposed on originally continuous smooth faces, clearly, this material was broken and chipped during some violent experience before deposition. The percentage of these broken rounds is far higher than in the Snake River gravel now in transit.

Close examination of the scabland complex shows that the basalt lava flows have been plucked, not abraded. Abrasion of large fragments to cobble and pebble sizes occurs mostly during stream transportation. Many large boulders lie but a short distance downstream from the channel-bottom outcrops of large-columned basalt, and many boulders still show columnar outlines. Only huge volumes of water released suddenly could have produced the "Channeled Scablands" (Bretz, 1969; Bretz, et.al., 1956).

Pardee (1942) discovered a series of descending arcuate asymmetrical ridges of flood transported debris lying transverse to the slope below Markle Pass and Will's Creek Pass in Camas Prairie, the ridges were interpreted as giant current ripples. He also noted such features as gulch-fillings, high eddy deposits, and severely scrubbed and largely bare-rock salients along the Flathead and Clark Fork Valleys. These strongly eroded surfaces are below the lake's upper limit, while the slopes above have a cover of soil and colluvium. He interpreted these land forms as resulting from huge volumes of water released from a collapsing ice dam at the north end of the Bitterroot Range. Pardee estimated that the maximum discharge was 9.5 cubic miles per hour.

After the first outflow, Pardee (1942) believes that ice again dammed the river forming another lake. Either the rapid outflow was greatly slowed when the first lake partly drained, or, if it had emptied, the basin soon became refilled; then this new body of water drained away slowly. Pardee (1910, 1942) interpreted Missoula's faint, closely spaced shorelines as evidence for a slow draining, for no lake stand was of long duration. Even the current-produced features in Camas Prairie have shorelines etched on them; another indication of subsequent quiet draining of the lake.

Davis (1921) doubted Pardee's (1910) interpretation of high eddy deposits and hypothesized that tongues of glacial ice, flowing under water up the Flathead and Clark Fork River Valleys, left fragmentary lateral moraines. He said that the ice did not float because it was tightly stuck to the valley floor. There is a major problem with this hypothesis: How were the lake sediments deposited between the ice and the valley floor? Obviously, Davis did not observe the lake sediments in these valleys, or he would not have made such an interpretation. He described the scrubbed rock salients as "roche moutonees": the orientation of the features also suggest that the ice moved upstream.

Alden (1953) has suggested that Lake Missoula formed and emptied two or three times. He also suggested that the scablands may have been produced even if the lake were only partially drained. However, he could not accept as flood-made, Pardee's giant current ripples in Camas Prairie. Alden (1953) explained these features as follows:

> There are other somewhat puzzling features... namely, a multitude of small ridges 5 to 50 feet high that are spread out on the low piedmont slope between the central flat of lacustrine deposits and the hills on the east and north... It seems to the writer, ... that some of these numerous small ridges are beaches or bars formed by the lowering waters of glacial Lake Missoula...

Alden (1953) did not make a careful study of the glacial lake silt, but noted that most of the silt is laminated and is of a very fine, even texture. He also noted that the pebbles are few and those present were probably dropped from floating ice.

Richmond and others (1965) have found evidence for nine glacial retreats in the Northern Rocky Mountain province; their evidence is based on "soil making intervals". These old soil markers have been traced into the Columbia Plateau and identified with the occurrence of three Lake Missoula floods. However, Richmond does not explain how nine soil horizons are correlated with three Lake Missoula floods.

It seems, however, if the Pend Oreille lobe reached the site of the Lake Missoula dam in each of the nine advances, as many burstings might be expected in the record (Bretz, 1969). Bretz, et.al. (1956) believe that the topography of the scablands records seven such floods, and that at least one additional flood occurred before a heavy caliche had accumulated; fragments of the caliche are seen in the flood gravels. If this is correct, then at least eight floods may have accompanied the nine glacial advances (Bretz, 1969).

Bretz (1969) reviews the outstanding evidence for (1) repeated catastrophic outbursts of Lake Missoula, (2) the Channeled Scabland complex, and other features produced by the flood waters of Lake Missoula. On the basis of the numerous faint shorelines, Bretz surmises that these are the aggregate result of numerous fillings and emptyings and not a strictly chronological series.

Bretz (1969) also outlined several unsolved problems in the history of Lake Missoula; one of which is of particular interest to the present writer. I am interested in the lake bottom sediments and according to Bretz, the lake sediments are only in the early stages of being deciphered. He also pointed out that only reconstruction of the Pend Oreille dam will produce another Lake Missoula and the sequences of varved clays will be separated by an unconformity. According to Bretz, carbon-14 dating of woody material appears to be the only reliable method of correlation among areally separated records of drainage intervals.

Chambers and Alt (1971) have found what they believe to be 37 stratigraphic units similar to those suggested by Bretz. Each unit consists of a basal layer of unvarved silts topped by a sequence of varved glacial lake deposits. At least half of these units are separated by recognizable weathered zones, none of which have well developed soil horizons. We have interpreted these units as recording 37 lake level fluctuations during the Pinedale substage.

Glacial History

During each Quaternary glaciation, the Cordilleran Ice Sheet pushed southward from Canada into the United States, covering much of the Northern Rocky Mountains west of the continental divide and extended south to about 47°30' Latitude (fig. 2)(Richmond, et.al., 1965).

During the Pleistocene; five glaciations, separated by interglacial periods, are recognized (table 1). The Bull Lake Glaciation is divided into two, and locally three, advances. The Pinedale Glaciation consists of three stages,

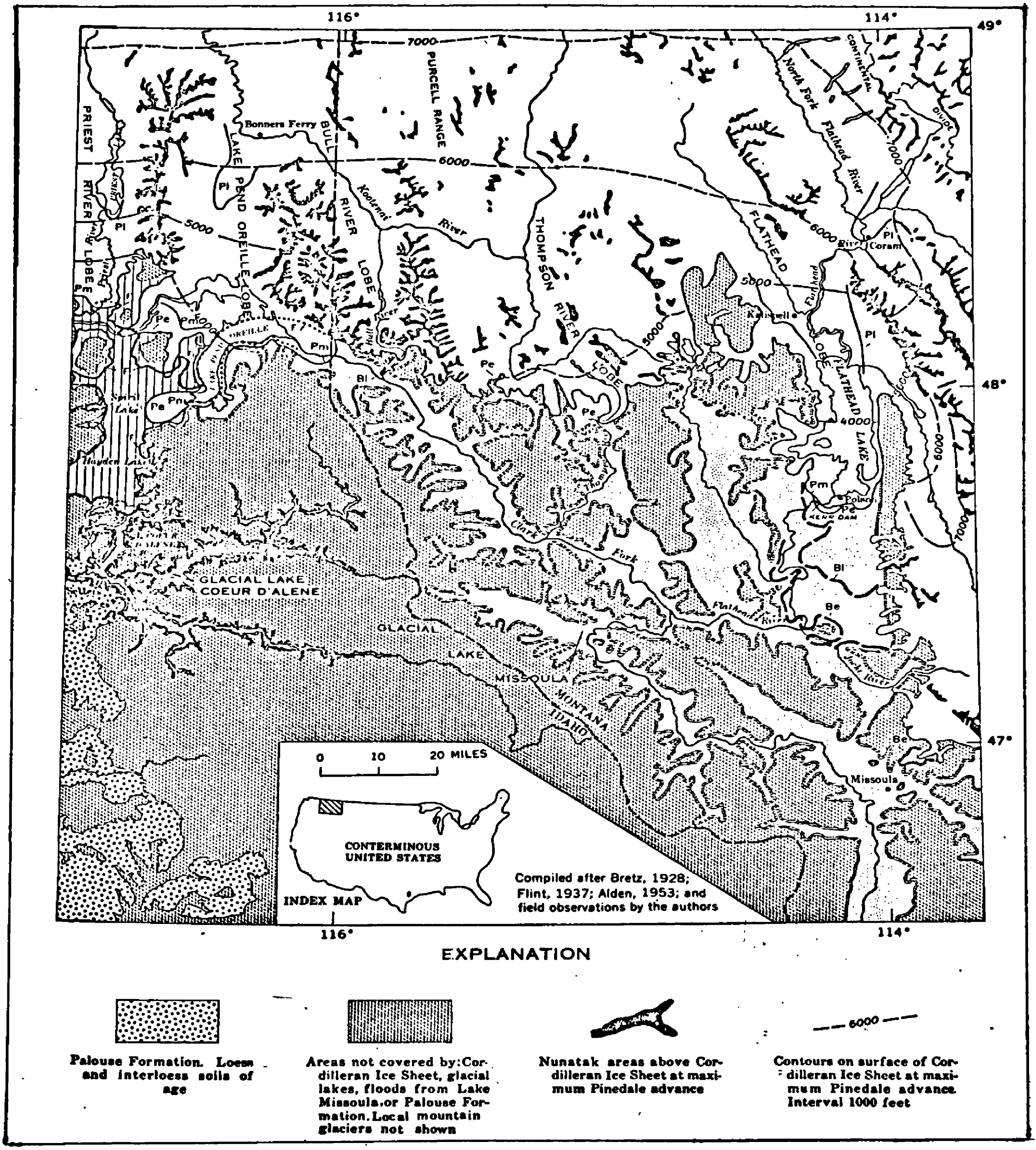


Fig. 2. Map of the Corilleran Ice Sheet of the Northern Rocky Mountains (from Richmond, et. al., 1965).

Approximate age B.P.	Alps of Europe		Approximate age B.P.	ROCKY MOUNTAINS Richmond (this paper)			Approximate age B.P.	Midcontinent Region After Frye & Willman (1960)		
	Post-glacial			Neoglaciation	Gannett Peak Stade			RECENT		
			800		Interstade					
			900		Temple Lake Stade					
			4,000	Altithermal interval			5,000	WISCONSINAN STAGE	VALDERAN SUBSTAGE	
6,500	Daun Gschnitz Schlern		6,500	Pinedale Glaciation	Late stade					
			10,000		Interstade					
11,000	Allerød Interval						11,000		TWOCREEKAN SUBSTAGE	
	Main Würm	Two Recessional moraines	12,000		Middle stade		12,500		WOODFORDIAN SUBSTAGE	several advances
		Interstade			Interstade					
		Outer moraine			Early stade		22,000		FARMDALIAN SUBSTAGE	
			25,000	Interglaciation			28,000		ALTONIAN SUBSTAGE	
29,000	Paudorf Interval		32,000	Bull Lake Glaciation	Late stade	2nd episode				
34,000	Early Würm									
45,000	Göttweig Interval		45,000			Nonglacial interval				
						1st episode	50,000 to 70,000 estimated			
53,000	Riss	Riss II								
		Nonglacial interval			Nonglacial interval			SANGAMONIAN STAGE		
		Riss I			Early stade					
	M/R Interglaciation			Interglaciation						
	Mindel Glaciation	II		Sacagawea Ridge Glaciation				ILLINOIAN STAGE		
		I								
	G/M Interglaciation			Interglaciation				YARMOUTHIAN STAGE		
	Günz Glaciation	II		xxxxxx(1) Cedar Ridge Glaciation				xxxxxx(1) KANSAN STAGE		
		I								
	D/G Interglaciation			Interglaciation				AFTONIAN STAGE		
	Donau Glaciation	III		Washakie Point Glaciation				NEBRASKAN STAGE		
		II								
		I								

Table 1. Correlation of the Glaciations of the Rocky Mountains with those of the Midcontinent and the Alps of Europe (from Richmond, 1965).

or minor advances, separated by brief interstadials. Final recession of the late Pleistocene glaciers was followed by a warm and dry episode known as the Altithermal interval, which in turn, was followed by the Neoglaciation of local alpine glaciation (Richmond, 1965) (table 1).

Alden (1953) recognized three glaciations in western Montana and northern Idaho; early pre-Wisconsin, Illinoian or Iowan, and two Wisconsin periods. Richmond (1965) and Richmond, et.al. (1965) have recognized four different glacial deposits separated by soil forming intervals. The oldest is a very deeply weathered drift and is probably pre-Wisconsin. Two intermediate tills stratigraphically separated by mature zonal soils are indicative of nonglacial conditions and are correlated with the early and late stages of Bull Lake Glaciation. The youngest deposit forms fresh bouldery moraines with immature zonal soils and mark a maximum and, one or more secondary advances correlated with the early and late stage of Pinedale Glaciation.

Richmond, et.al. (1965) suggest that the highest lake stands occurred during the Bull Lake and early Pinedale Glaciations (table 2). During early Bull Lake, the Flathead Lobe reached its most southerly extent near St. Ignatius (fig. 2), and occupied a major portion of the Mission Valley. The Mission moraine, near Ninepipe, appears to be a composite moraine probably occupied by ice during the late Bull Lake and early Pinedale Glaciations

Approx. years B.P.		ROCKY MOUNTAINS	Glacial chronology after Richmond (this volume)	CORDILLERAN GLACIATION: Eastern Washington, Bretz (1923 1928)	Eastern Washington, Flint (1935 1936 1937)	Western Montana, Alden (1953)		Recognized in this paper	GLACIAL LAKES: Lake Missoula (Dammed by Pend Oreille ice lobe at Clark Fork)	Lake Coeur d'Alene (Dammed by Pend Oreille ice lobe at Coeur d'Alene)	Lake Spokane (Dammed by Colville ice lobe at Spokane River)	Lake Columbia (Dammed by Okanogan ice lobe at Grand Coulee)	COLUMBIA PLATEAU: Lo[illegible] and soils	Catastrophic floods	PACIFIC NORTHWEST: Glacial chronology after Crandell (this volume)
	RECENT	Neoglaciation	Gannett Peak Stade					Local cirque moraines and rock glaciers					Very weak soil		Neoglaciation
600			Interstade										Pale loess Very weak soil		
900 4,000			Temple Lake Stade										Pale loess		
			Altithermal interval					Moderately developed soil	Moderately developed soil	Present level of lake (2,125 ft.) attained by gradual lowering	Moderately developed soil	Moderately developed soil	Weakly deve[illegible]ped soil	Weakly developed soil	Hypsithermal
6,600			Mt. Mazama ash					Mt. Mazama ash	Mt. Mazama ash		Mt. Mazama ash	Mt. Mazama ash	Mt. Mazama ash	Mt. Mazama ash	Mt. Mazama ash
	PLEISTOCENE	Pinedale Glaciation	Late stade	Wisconsin Glaciation	WISCONSIN GLACIATION	Wisconsin	Recession	Recessional gravel	Gradual withdrawal				Pale loess		interval (9,000)
							Kalispell Moraine	End moraine	Flathead Lake at 3,200 ft.						Sumas Stade
10,000			Interstade				Recession	Recessional moraine	Gradual withdrawal				Weakly develo[illegible] soil		(11,000)
12,000			Glacier Peak ash					Glacier Peak ash					Glacier Peak ash	Glacier Peak ash	Everson Interstade
			Middle stade				Polson Moraine	End moraines	Lake rise to +3,850 ft.	Retained by flood gravel at 2,300 ft.		Nespelem terrace 700 ft ice dam recedes Lake surface 1,950 to 1,800 ft	Pale loess	Final flood on Columbia River	Fraser Glaciation (13,500) Vashon Stade
			Interstade					Recessional gravel	Catastrophic flood withdrawal	Catastrophic flood to 2,665+ ft.	Catastrophic flood deposits	Catastrophic flood deposits	Catastr[illegible] erosion Tou[illegible] Beds	[illegible]atastrophic flood deposits of Lake Missoula	Recession
			Early stade					End moraine	Lake rise to 4,200 ft.	Lake surface −2,400 ft.		Lake surface at 1,950 ft	Pale loess		Evans Creek Stade
25,000			Interglaciation			Deep weathering		Strongly developed soil	Strongly developed soil		Disconformity	Disconformity	[illegible]	Strongly developed soil	[illegible] interglaciation
32,000		Bull Lake Glaciation	Late stade: 2nd episode	Spokane Glaciation		[illegible] or Iowan	Mission Moraine	Till	Lake rise possibly to 4,400 ft.	?	?		[illegible]	Flood deposits from Lake Missoula Flood deposits from west	[illegible] glac. episode
45,000			Late stade: Nonglacial interval			Deep weathering		Disconformity	Disconformity						
50,000			Late stade: 1st episode			Earlier pre Wisconsin	Earlier advance	Till	Lake rise to 4,400 ft.	Ice dammed at 2,400 ft.	Surface at 2,350-2,400 ft.	Lake surface at 2,350(?) ft.	[illegible]		
			Nonglacial interval					Strongly developed soil	Strongly developed soil	?	?	?	[illegible] developed soil		nonglacial int.
			Early stade					Till proglacial gravel	Lake rise to 4,400 ft.				Brown [illegible]		Older glacial episode
			Interglaciation					Very strongly developed soil	(Valley floor at Bull Lake ice dam 2,200 ft. alt.)	(Valley floor at Bull Lake ice dam 1,800 ft. alt.)	(Valley floor at Bull Lake ice dam 1,400 ft. alt.)	(Valley floor at Bull Lake ice dam 850 ft. alt.)	Very [illegible] developed [illegible]	Very strong developed soil (Caliche)	Puyallup interglacial
			Sacagawea Ridge Glaciation					Till					[illegible]	Flood deposits [illegible] Lake Missoula	Stuck glaciation: 2nd ep. 1st ep.
			Interglaciation										Very strongly developed [illegible] caliche Oxidized tuff		Alderton Interglacial
			Cedar Ridge Glaciation										Ringold Formation (in part)		Orting Glaciation: 3rd episode
			Interglaciation												2nd episode
			Washakie Point Glaciation												1st episode

Table 2. Correlation of Deposits and Events of the Corilleran Region and Columbia Plateau (from Richmond, et. al., 1965).

(fig. 2). The water probably did not attain depths as great as those during early Bull Lake time (table 2). The Polson moraine marks the farthest advance of the Flathead Lobe during the late Pinedale stage (fig. 2). Since this was a time during the waning stages of glaciation, with reduced precipitation, the lake was probably rather shallow at this time. Strandlines at approximately the 3400 foot contour interval, on the Polson moraine, give an indication of the highest lake stand during late Pinedale time. Another indication of shallow water depths, during late Pinedale time, is that most of the shorelines appear to have patterned ground developed on them (R.R. Curry, oral communication, 1971). Patterned ground would develop only under periglacial conditions at times of glaciation.

Lake Missoula and its Relation to the Glaciation

The varved silt deposits, composed of glacial rock flour, were derived from the pre-Wisconsin and Wisconsin age Cordilleran Ice Sheet. Four lobes of Cordilleran ice supplied most of the sediment to Lake Missoula to the northern portion of the lake. One lobe, the Pend Oreille, not only supplied sediment to the lake, but dammed the Clark Fork River forming Lake Missoula to the east (fig. 2). During Bull Lake time, the Pend Oreille Lobe advanced down the Purcell Trench, across the Clark Fork River, as far south as Spokane. The ice border is marked east of Spirit

Lake (fig. 2) by a lateral moraine eroded by flood waters, and at Hayden Lake it is marked by a moraine with a mature reddishhbrown clayey soil covered by flood deposits (Richmond, et.al.,. 1965).

During both the early and late stages of Pinedale Glaciation the Pend Oreille Lobe again dammed the Clark Fork River. It extended eastward up the Clark Fork to the Idaho state line, merging with local alpine glaciers, impounding Lake Missoula behind it (Alden, 1953). End moraines of the early stage were mostly destroyed by catastrophic flood water from Lake Missoula. Undistrubed moraines of the late stage lie across the path of the flood (Richmond, et.al. 1965). This lobe of ice supplied large amounts of sediment to the far northwestern part of the lake.

The Bull River Lobe, just east of the Pend Oreille Lobe, flowed down the Bull River, during Bull Lake time, reaching the mouth of the valley where it joins the Clark Fork River. An end moraine, thickly mantled with flood deposits, about 3 to 5 km upstream, is indicative of the early Pinedale advance of the Bull River Lobe. This lobe of ice also supplied sediment to the far northwest part of the Lake.

A large lobe of ice, the Thompson River Lobe, flowing down the Kootenai River east of the Purcell Range reached its maximum southerly extent, during Pinedale time, just north of the Little Bitterroot Valley. This lobe supplied sediment to both the Little Bitterroot Valley and the northern part of the Mission Valley (Richmond, et.al., 1965).

Glacial lake deposits conformably overlie tills recording three advances of the Flathead Lobe during Bull Lake Glaciation: one of these advances may be pre-Bull Lake (Richmond, et.al., 1965). The two high stands of the lake at 4400 feet have been correlated with the two earlier advances during Bull Lake time (table 2). Each suite of lake sediments consists of a lower unit of varved clayey silt indicating glacial recession; a disconformity, overlain by an upper unit of lake sand and massive silt suggesting glacial readvance (Richmond, et.al., 1965).

The early and late Pinedale advances of the Flathead Lobe are marked by terminal moraines near Polson, which intertongue with and are overlapped by lake deposits. The moraines have strandlines developed on them, indicating that they were formed subaerially and later covered by water (Alden, 1953, Richmond, et.al., 1965).

The Mission Valley received most of its sediment from the Flathead and Thompson River Lobes. An unknown, but possibly large amount of this material came from the local alpine glaciers in the Mission Range. Extensive deposits of silt are found along the Flathead River from Kerr Dam to Dixon. Silt terraces over 150 feet high occur just north of Moiese (Alden, 1953). The silt in the Plains basin came from either or both the Mission and

Missoula-Ninemile basins. There are limited exposures of silt in the Perma and Paradise narrow, this sediment was probably derived from the Bull River and Pend Oreille Lobes (Pardee, 1942; Alden, 1953).

The lake sediments in the Missoula-Ninemile basin are believed to have been derived from the Blackfoot and Rattlesnake glaciers with a minor contribution from glaciers emptying into the Bitterroot Valley. The bulk of the material probably came from the Blackfoot Valley glacier, its farthest advance is marked by a terminal moraine at Clearwater, approximately 35 miles northeast of Missoula. The Blackfoot Valley is underlain by Precambrian Belt rocks which in turn are overlain by Tertiary rocks (Sieja, 1959). The terminal moraine of the Rattlesnake Valley glacier is approximately 5 miles north of Missoula (Alden, 1953; Pardee, 1942). The silt forms extensive terraces between Missoula and Huson. However, little silt is now found in the Bitterroot Valley and the valley of the Clark Fork above the mouth of the Blackfoot River, because these areas received meltwater only from local alpine glaciers (Alden, 1953). The Jocko Basin received sediment from silt released into the lake from glaciers in the upper Jocko Valley (Pardee, 1942).

Although widespread, the lacustrine sediments are not coextensive with the maximum area of the lake. The silt is confined to the lower parts of the basins and thins up the valley sides. The lake sediments are seen today as discontinuous, erosional terraces, 50 to 150 feet high, in most of the basins (Pardee, 1942; Alden, 1953).

Pardee (1942) suggests that deposition of the silt is limited to the lower parts of the basins because it moved by turbidity currents, owing to its greater specific gravity, and flowed along the bottom without mixing with the overlying clarified water. In order for silt to reach the Plains Basin, it must have been carried 50 to 75 miles from its sources in glaciers discharging their meltwater in the Mission and Missoula-Ninemile Basins.

Professor David Alt has pointed out (oral communication, 1971) that the silt in the Missoula Valley seems to be localized around the mouth of Evaro Canyon. He suggests that this localization is the result of turbidity currents flowing out of the Jocko Basin, with its source area in the Mission Valley. I have yet to find any silt near the mouth of the canyon or in the immediate vicinity. It seems more logical that sediment came from a more local source area, the Blackfoot Valley glacier, and not from the Mission Valley. If one looks closely at aerial photographs one can see prominent meander scars, from the Clark Fork River, just east of Evaro Canyon. I suggest that most of the sediment east of the canyon has been eroded away since the end of the Pleistocene, and any localization of sediment is coincidental.

CHAPTER 2

PRESENT INVESTIGATION

Location of Project Area

Lake Missoula occupied six major intermontane basins in western Montana (fig. 2). Specific outcrops were studied in the Missoula-Ninemile Valley, Camas Prairie, and the Jocko Valley. Although the sediments are well exposed throughout the valleys, deep mechanical weathering and slumping makes section measuring difficult at most localities.

X-Ray Diffraction Results

No vertical variation in the clay suite could be detected. Each sample contained a highly expandable (>70%), randomly interstratified illite/smectite, illite, kaolinite, some quartz and feldspar. The illite/smectite is apparently coming from Tertiary rocks and not Belt rocks (Thompson, oral communication, 1971). No chlorite reflection appeared in the less than one micron size fraction.

After glycolation of the potassium hydroxide treated sample, the 17Å peak (illite/smectite) collapsed to an apparent 14.5 Å peak. This reaction suggests a minor component of vermiculite in the less than one micron size fraction. More work needs to be done in order to prove the presence of vermiculite.

Sieja (1959) used size fractions of less than two microns. Chlorite is present in this size fraction, but he saw no response to KOH treatment. He also found, in order of decreasing abundance, illite, smectite, chlorite, and kaolinite. Illite and chlorite are more abundant in the dark winter layers, while smectite and kaolinite are more abundant in the light summer layers of the varves. Sieja (1959) interpreted this seasonal segregation of clay minerals as resulting from differential sedimentation by differences in the rates of flocculation of the clay minerals. He also found a lateral increase in illite and decrease in smectite with increasing distance from source area, which he also attributed to differential sedimentation.

Calcium Carbonate Results

Only one weathered zone, V20-1, shows a significant enhancement in calcium carbonate (table 3). This zone probably represents a longer period of subaerial exposure, during warmer, drier conditions. It is possible that this zone represents nonglacial conditions during the Bull Lake-Pinedale interstadial. More work needs to be done on these weathered zones.

Radiocarbon Results

Approximately 1 gram of woody fragments was collected from the basal festooned sands in silt unit 2 at locality

Unit/sample	Weight before	Weight after	% $CaCO_3$
S19-1	58.259	55.944	3.974
V18-1	42.719	40.946	4.150
V18-2	37.661	36.076	4.209
S15-1	55.869	51.900	7.104
V14-1	40.123	38.662	3.642
V14-2	47.098	45.429	3.544
S21-1	79.021	74.576	5.625
V20-1	54.020	13.097	75.755
V20-2	23.649	22.017	6.901

Table 3. Results of calcium carbonate analysis S means silt; V means varves; V18-1, V14-1, and V20-1 are weathered zones.

MV-1. This outcrop is located approximately 3 miles west of the Kalispell-Glacier Park turnoff (highway 93) along Highway 10 on the north side of the road.

Because of the presence of uranium or some other naturally radioactive element mixed with the sample, it was impossible to obtain a C^{14} date.

Varve types

Several different types of varves were recognized during the course of study; they are classified, with modifications and additions according to Antevs (1951) and summarized in Table 4 .

Each varve consists of a lower light and an upper dark layer. The light layer is classically interpreted to represent spring and summer deposition, while the dark layer formed during fall and winter, so that each pair records an annual deposit (De Geer, 1884; from Antevs, 1922). The light layers contain more silt-size material than clay, while the darker layers are rich in organics and have more clay than silt (Sieja, 1959). Varved thicknesses are controlled by seasonal variations; thick varves are representative of exceptionally warm summers, while colder years produce thinner varves (Antev, 1951). Each of the varve types may be identified descriptively and genetically interpreted.

Steep Rock Lake Varves

Antevs (1951) described simple varves as those having distinct light summer layers and dark winter layers. Some of the simple varves have a second thin, wispy, light colored silt layer within the dark winter layer; probably recording a winter thaw. Simple varves are believed to have formed under low temperatures, weak thermal stratification, and quiet circulation of the lake water.

Kuenen (1951) and Antevs (1951) believe that density underflows are probably important in forming varved clays. The light components of varves were probably deposited as turbidity currents flowing along the lake bottom, while the winter laminae were formed from mud carried along the water surface or mixed with the lake water. Turbidity currents can explain the vertical sorting seen in the varved clays (fig. 3).

Composite varves contain thin dark clay laminae within the light summer component, making subordinate couplets resembling thin or faint true varves. Antevs (1951) interpreted these as resulting from strong intermittent mud inflows and quick deposition of the silt that entered a strongly thermally stratified lake. The settling of the clay may have been delayed slightly after it was carried to great depths before deposition. The number of subordinate couplets depended on weather changes, influx and rate of mud deposition and length of summers. Because of these

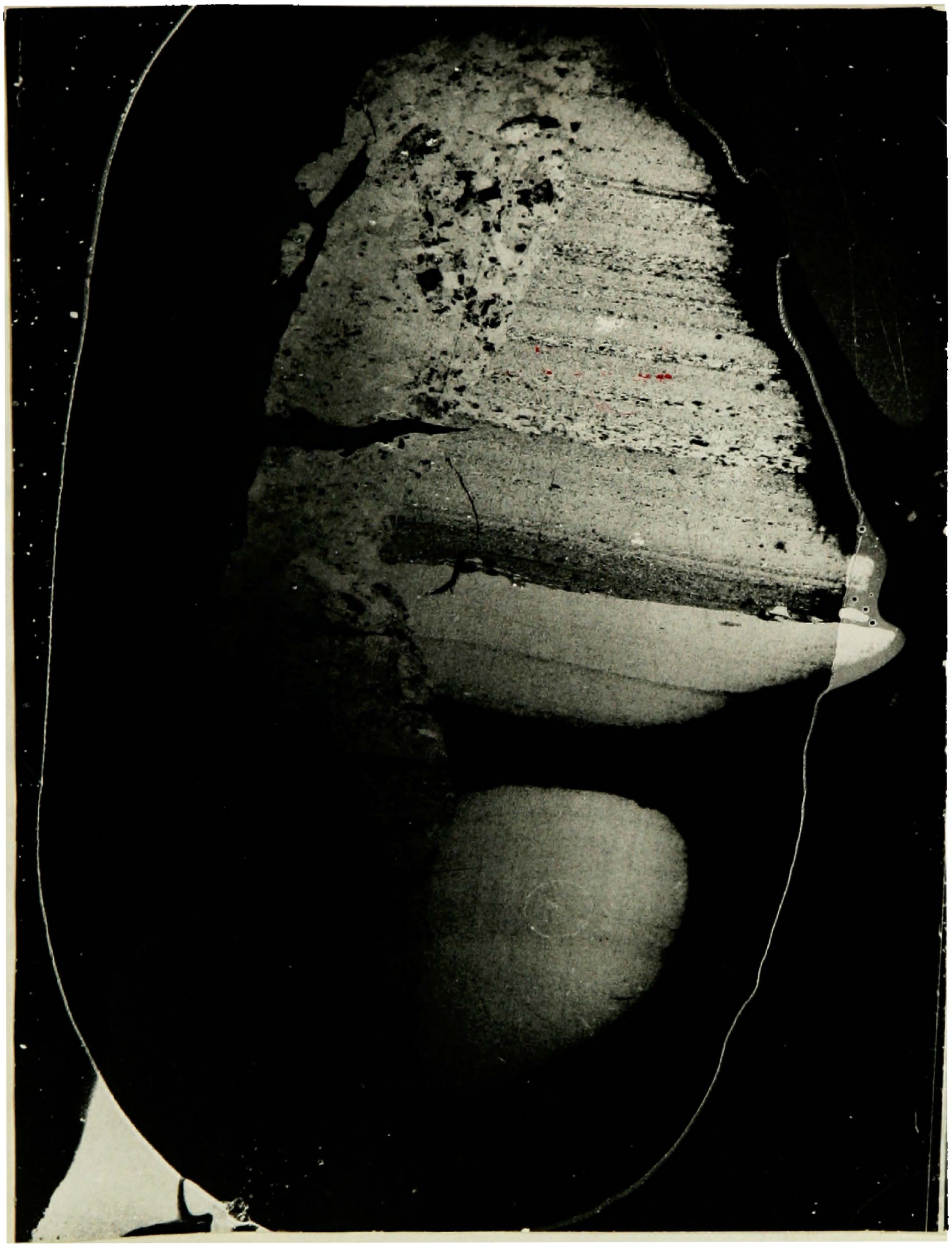


Fig. 3. Thin section showing vertical sorting in varves.

special conditions, composite varves are local and exceptional.

Antevs' varved sequences are sporadically broken by unvarved laminated beds. The unvarved laminations consist of numerous obscure, wispy, dark laminae within a thick light layer. According to Antevs (1951) these are the result of too little clay material in the lake water, at the end of a melt season, and a true varved sequence did not develop. These unvarved laminations are rare, and products of both variable mud inflow and isothermy of the lake water.

Antevs (1951) also recognized abnormally thick simple varves and termed them drainage varves. He interpreted them to represent excessive influxes of material, into a settling basin, from failure of an ice or earth dam upstream.

Lake Missoula Varves

Most of the varves in Lake Missoula are simple, but composite varves also occur (fig. 4). The simple varves of Lake Missoula are descriptively similar to those described by Antevs and presumably form under similar conditions.

Simple varves may be characterized as follows; the basal contact of each light summer component sharply overlies the dark winter component of the preceeding varve.

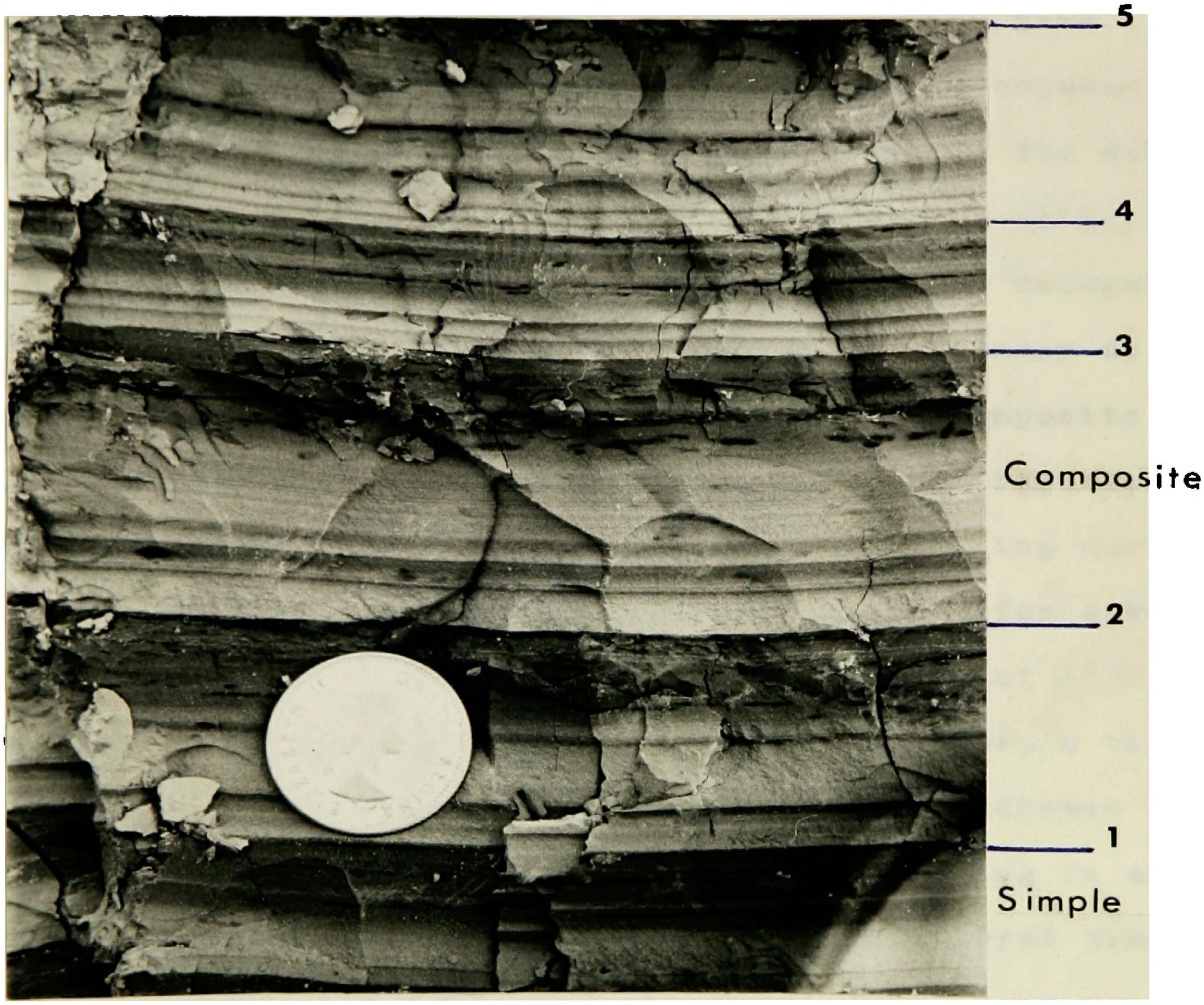


Fig. 4. Simple and composite varves in unit 7 at locality SP.

However, the light layer grades upward into the dark layer, and it is impossible to separate sharply the two components in a single couplet.

Composite varves, similar to those described by Antevs, are also common in Lake Missoula sediments. They have numerous thin, dark laminae within their summer component which in turn grades into the dark winter layer. The subordinate laminae, when viewed as pairs, look like thin, true varves. Like simple varves, composite varves are recognized by sharply defined bounding planes. Although as many as 37 subordinate couplets were measured in a single composite varve, they average about 6. I believe that subordinate couplets are formed by periodic freezing and thawing during the summer months. If the weather became colder for a week or more during the summer, decreasing the amount of silt discharged into the lake and killing surface algae, a thin, dark lamina would be deposited. Warming would increase the amount of silt released into the lake resulting in another light layer. If this process occurred several times during the spring and fall, and the final dark layer was deposited during the fall and winter, a composite varve would have been formed. As Antevs suggested that the number of subordinate couplets per varve depended on weather changes and length of summer. Strong thermal mixing in the lake water may result from periodic freezing and thawing; this could possibly affect the deposition of the suspended clay material; the cold surface water, because of its greater density, would bring the clay down closer to the lake bottom.

Although unvarved laminations are absent in Lake Missoula, abnormally, thick dark brown, clay layers, containing obscure, wispy light silt laminae do occur. These may represent long periods of cold temperatures, decreased glacial melting, with subsequent decrease in the amount of silt released into the lake. These layers represent unknown numbers of years.

Another type of unvarved sediment, unlike any in Steep Rock Lake, also occurs in Lake Missoula. It forms unusually thick beds consisting mainly of silt-sized material. Although these are not varves, they are included in this classification. The silt layers will be discussed in more detail in the next section of this paper.

Type	Description	Antevs' Interpretation	Chambers' Interpretation
Simple; Antevs and Chambers	light summer layer and dark winter laminae; may have a second thin wispy silt layer within the winter layer	formed under low temperatures; weak thermal stratification, and quiet circulation of the lake water	formed by the same process
Composite; Antevs and Chambers'	thin dark laminae within the summer component; look like true varves	result of strong intermittent mud inflows and quick deposition of the silt; strong thermal stratification of the lake water	periodic freezing and thawing during the summer months, forming pseudo-winter laminae in the summer component
Unvarved laminations; Antevs and Chambers	thick light layer containing numerous obscure wispy dark laminae	due to variable mud inflows and isothermy of the lake water	absent in Lake Missoula

Table 4. Summary of Varve Types (continued on the next page).

Type	Description	Antevs' Interpretation	Chambers' Interpretation
Drainage; Antevs	abnormally thick simple varves	result from excessive sediment coming into a settling basin	absent in Lake Missoula
Thick, dark clay layers; Chambers	thick, dark layer containing numerous, obscure wispy, light layers	absent in Steep Rock Lake	period of long cold temperature resulting in decreased melting of the glacier and decreased discharges of silt released into the lake
silt layers; Chambers	unusually thick deposits of silt-sized material with many types of sedimentary structures	absent in Steep Rock	shallow water density underflows

Table 4. Continued from Page 28.

CHAPTER 3

DISCUSSION OF EXPOSURES

General Statement

The exposures of lake sediments may be divided into stratigraphic units. Each unit consists of a basal layer of unvarved silt overlain by a varve sequence (fig. 5). Unless indicated, the discussion of the stratigraphic units and sedimentary structures is limited to locality SP (see Appendix III). There are 40 stratigraphic units; the silt layers range in thickness from 5 cm to 160 cm, but average about 31 cm. The average number of varves in each varve sequence is 27, ranging from 9 to 58 in number. A total of 716 varves were counted at locality SP. The age of these sediments will be discussed in more detail in a later section, but are probably late Pinedale in age.

Most of the unvarved silts contain planar beds; and some ripple, dune and antidune crosslaminations. Wave ripple laminae, curl flow structures (Arlee outcrop, see Appendix III), and flame structures frequently occur at the base of the silt layers. The silt layers grade into the overlying varve sequence which frequently appears to be weathered, because of its dry, crumbly texture. The upper surface of each varve sequence is scoured, making any count of the varves a minimum number.

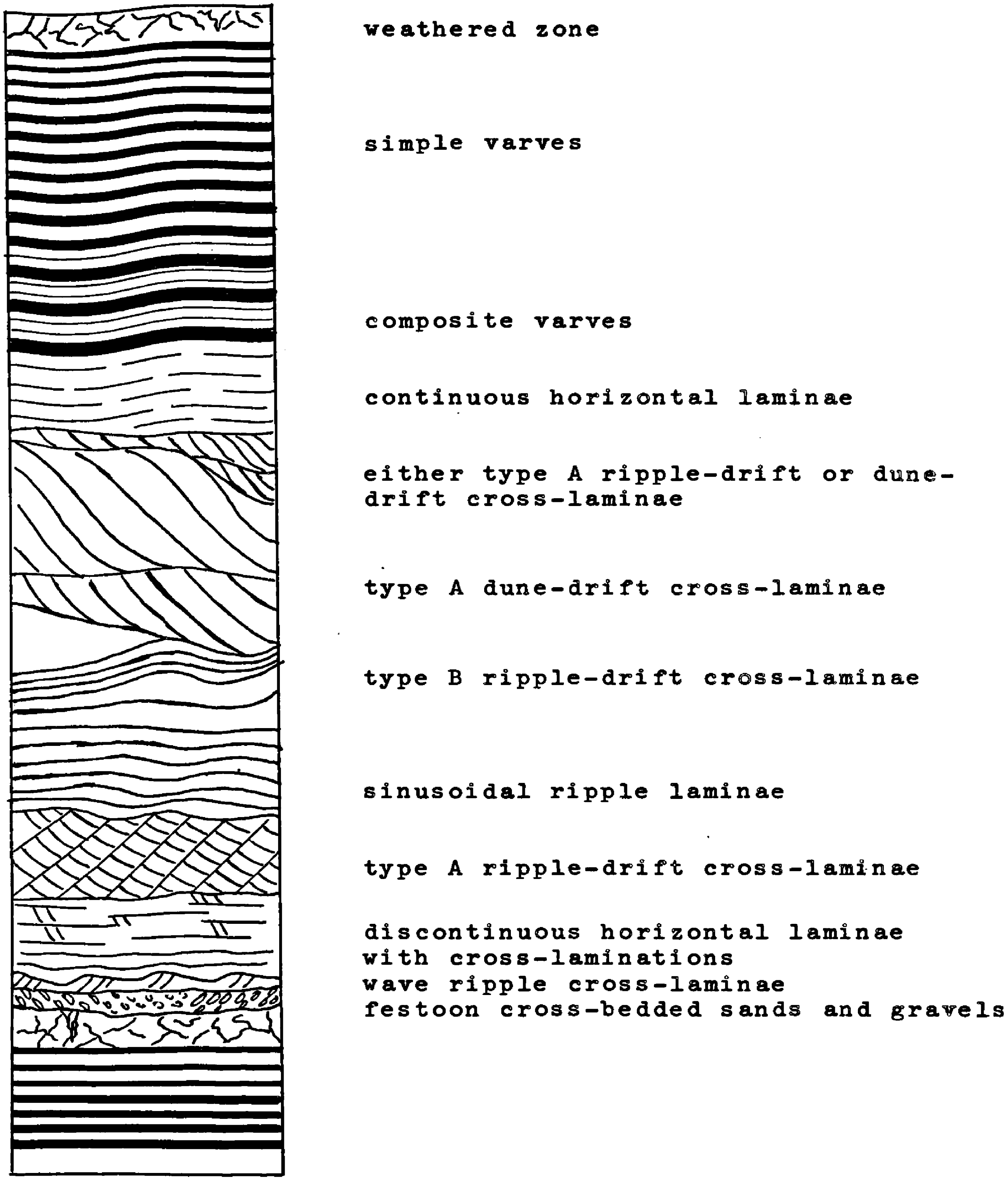


Fig. 5. Diagrammatic composite sedimentary unit.

Interpretation of Sedimentary Structures in the Silt Layers

Chambers and Alt, 1971; Alt and Chambers, 1970 suggest that the silt layers were deposited by streams. However, I now believe they were deposited by shallow water density underflows as described by Jopling and Walker, (1968). Reasons for this new interpretation are discussed in a later section of the paper.

Types of Ripple-Drift Cross-Laminations

Most of the cross-laminations are of the ripple-drift type. Ripple laminae are internal sedimentary features, whereas ripple marks are surface forms. Ripple-drift laminae form where deposition is rapid, so that the ripple marks build upward rather than simply migrate down-stream, leaving no record. In 1963, Allen (from McKee, 1965) explained the relationship as follows, "The rate a moving ripple surface builds up is directly proportional to the rate at which the sediment is deposited on it from an external source, thought to be the load sediment in suspension," and "The cross-stratification character...is dependent both on the rate of deposition from suspension and the ripple velocity."

Ascending ripple laminae only form when the rate of deposition is great enough to build overlapping series and under lower flow regime. Several types of ripple drift laminations were recognized and are referred to the nomenclature of Jopling and Walker (1968) and summarized in Table 5 .

Type A. - This type of cross-lamination (fig. 6), has only climbing sets of lee side laminae with no preservation of stoss side laminae. The lee side laminae are either concave-up or sigmoidal in shape, depending on how much erosion has taken place on the stoss side. Small concentrations of mica occur near the base of the slip face.

Type B. - These are composed of climbing sets of lee side laminae with complete preservation of stoss side laminae, and continuity of laminae from one ripple to the next. There is no gradual decrease in ripple amplitude upward. Some mica is concentrated at the base of the slip face (fig. 6).

Sinusoidal ripple laminations. - These laminations consist of superimposed undulating laminae, usually with slight dis-

Feature	Type A	Type B	Sinusoidal laminations
Laminae	preserved on the lee side only	continuous from the stoss side to the lee side	continuous from the stoss side to the lee side
Sediment	fine sand and silt with some mica near the slip face	fine sand and silt with some mica near the slip face	silt with no concentration of materials on particular parts of the ripples
Ripple Morphology	asymmetrical, variable amplitude	asymmetrical, variable amplitude	symmetrical, sinusoidal profile
Grading of Coset	ungraded	ungraded	ungraded

Table 5. Characteristics of different types of ripple-drift cross-laminations, after Jopling and Walker, 1968.

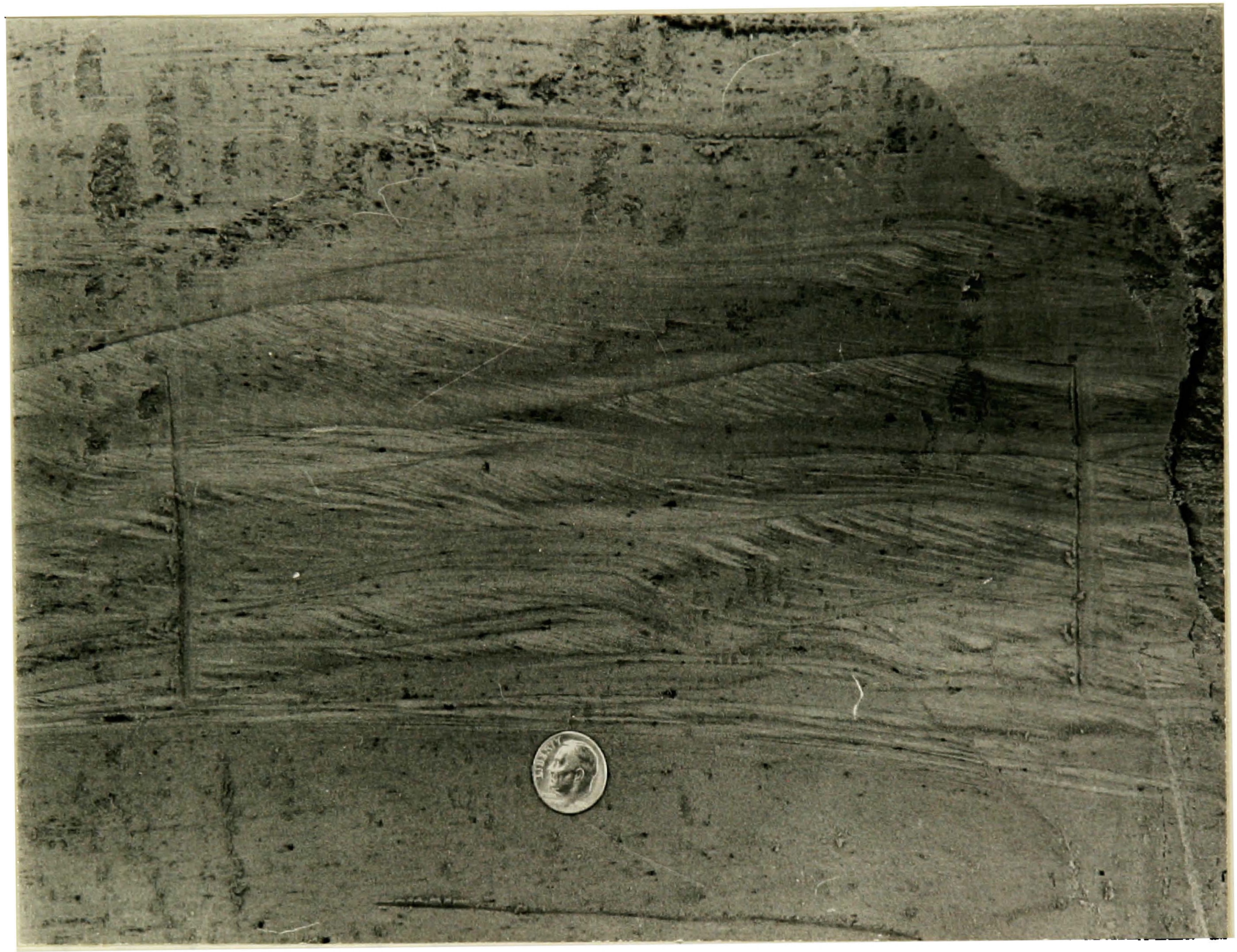


Fig. 6. Type A and B ripple-drift cross-laminations. Apparent direction is from left to right.

placement in the current direction. The lee and stoss sides are approximately equal in thickness with no concentration of material along the ripple surface (fig. 7).

Genetic Relationships of Ripple Drift Cross-Laminations

The genetic relationships deduced by Jopling and Walker (1968) are summarized in figure 8. The primary factor controlling the changing type is the ratio of suspended to traction load.

The preservation of only lee side laminae in type A suggests that fall out from suspension was minimal, and the grains on the stoss side were not buried. The suspension/traction ratio is very low (Jopling and Walker, 1968).

Sinusoidal ripple laminations were formed during minimal traction-load movement and maximum suspended load deposition. This interpretation is indicated by the continuity of laminae across the ripple system and fairly uniform thickness of the beds. Type B is intermediate between the two end members, because its morphology suggests that traction-load movement and deposition from suspension were equally important in its formation (Jopling and Walker, 1968).

Fig. 7. Sinusoidal ripple laminations at locality JV. Apparent current direction from right to left.

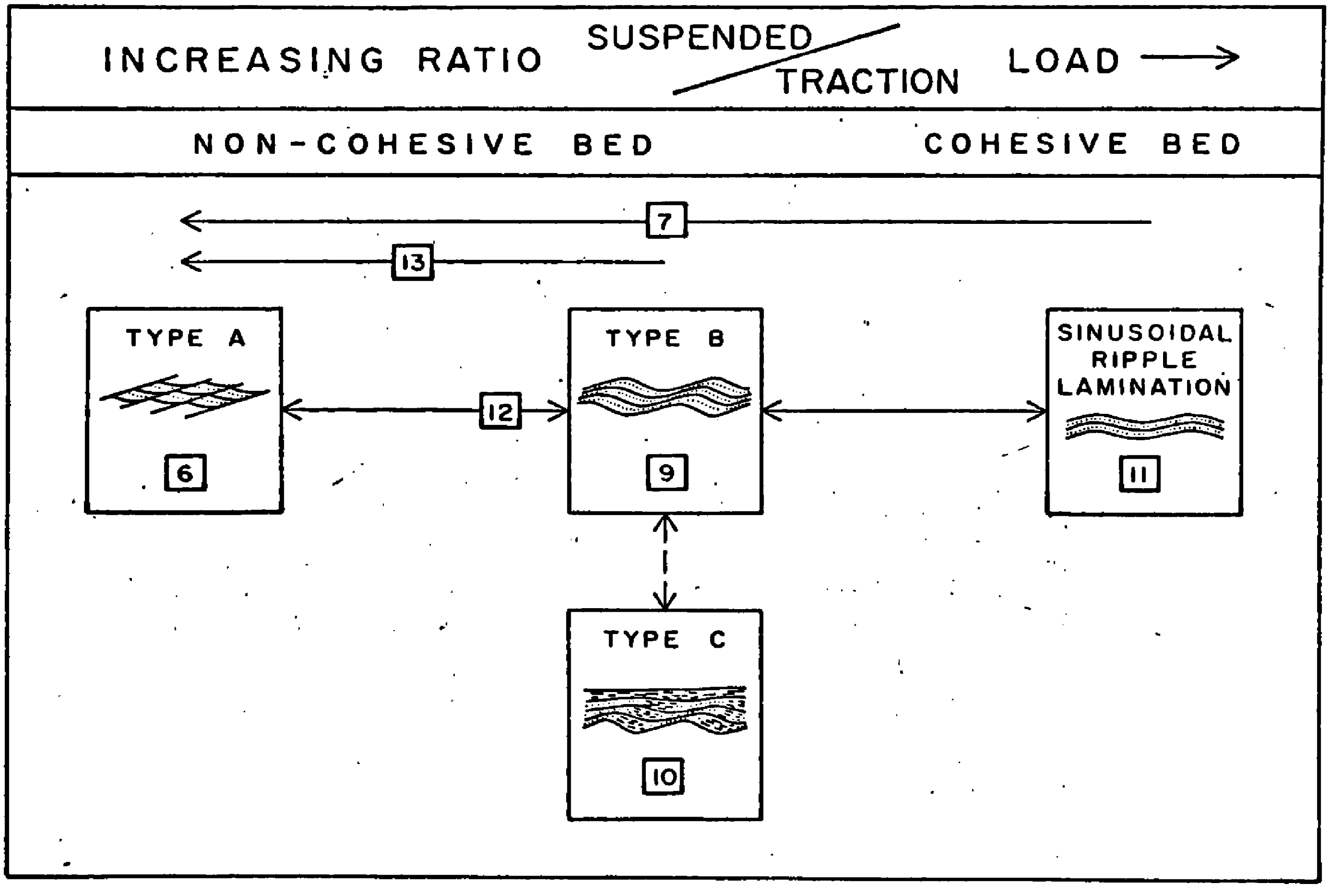


Fig. 8. Classification of ripple-drift cross-lamination based upon ratio of fallout from suspension to bed load movement by traction. Type C is not included in my classification (from Jopling and Walker, 1968).

The development of any one characteristic ripple form requires a certain persistence of a given set of sediment and current parameters; in particular the ratio of deposition from suspension to traction-load movement and current velocity (Jopling and Walker, 1968).

Another type of ripple lamination was recognized in the basal part of the silt layers. The crests of these asymmetrical ripples are fairly straight and parallel, suggesting that they are wave ripples formed by breaking waves and transport of material. An average wavelength is about 3.5 cm with an amplitude of 6 mm (fig. 9).

Planar Laminations

Two types of planar laminations were recognized: 1) continuous horizontal laminations, and 2) discontinuous horizontal laminations with cross-laminations. Continuous horizontal laminations are plane beds formed during transitional flow (Simons, et.al., 1965). The sets of horizontal stratification are usually thin, ranging from several millimeters to several centimeters. The lower boundary of each set is erosional, nearly horizontal or slightly irregular. The upper boundaries are also horizontal and planar (Harms and Fahnestock, 1965). These are the most common type of structure in silt layers.

Discontinuous horizontal laminations form during lower

Fig. 9. Wave ripple-laminae in silt layer 4 at locality SP. Apparent current direction is from right to left.

regime flow by ripples migrating rapidly downstream leaving only thin, horizontal layers. These layers are broken by small sets of ripple cross-laminae, probably due to momentarily increasing deposition (McKee, 1965).

Dunes

Larger scale cross-laminations occur near the top of silt unit 9. The wavelength ranges from 20 to 30 cm, and the amplitude from 6 to 10 cm. The dune laminae, like ripple laminae, build overlapping series and probably form under conditions similar to ripple laminae. Dunes form during upper-lower regime flow (Harmes and Fahenstock, 1965; Simons, et.al., 1965). The wavelength depends on the water velocity, while the amplitude depends on depth of water. Two types of dune-drift laminations were recognized and classified after Jopling and Walker's (1968) ripple-drift laminations.

> Type A. - Only lee side laminae are preserved, but are of a larger scale than type A ripple drift. Mica tends to concentrate near the base of the slip face (fig. 10).
>
> Type B. - Both the lee and stoss side laminae are preserved in this type. Mica tends to concentrate near the

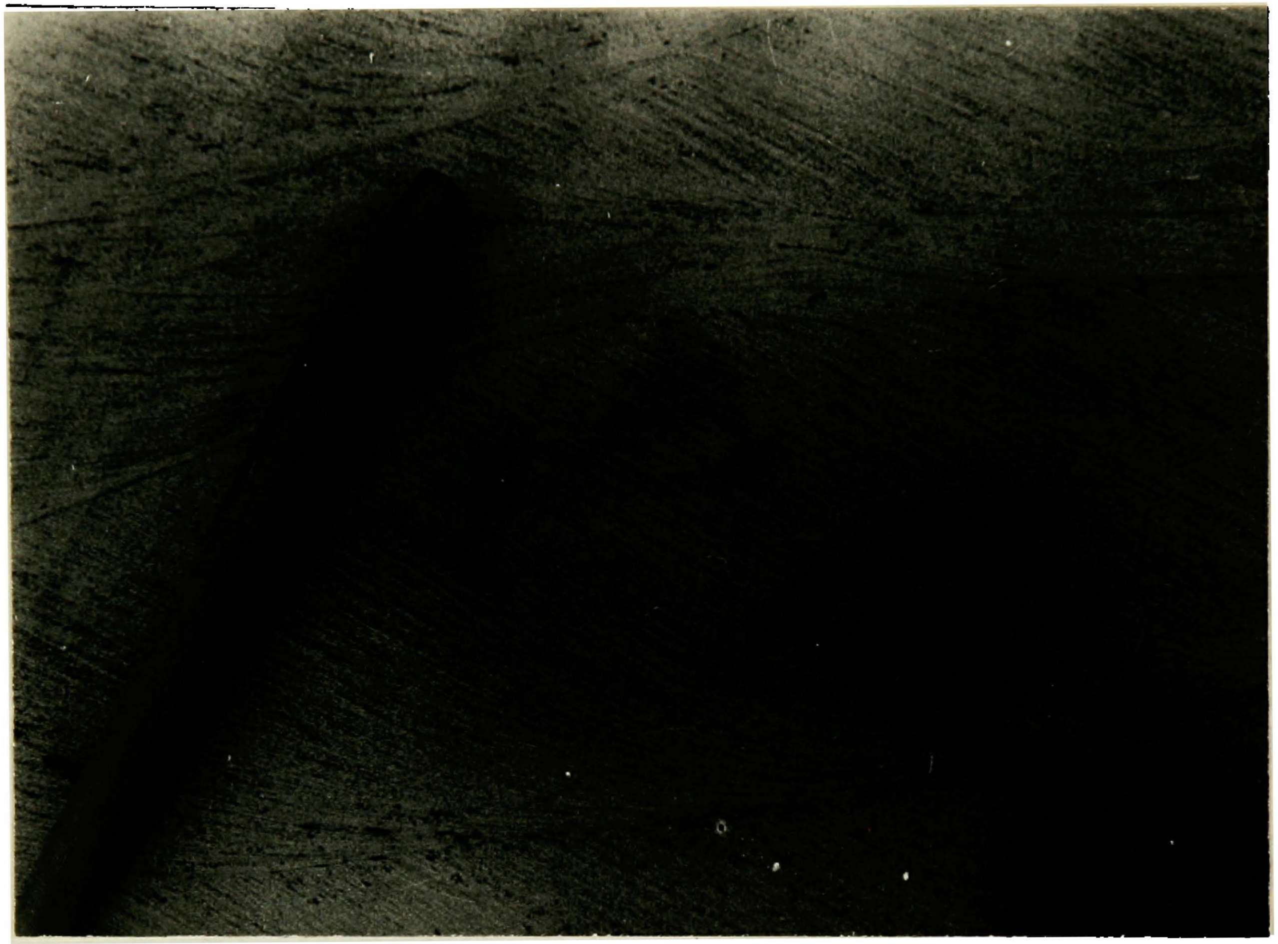


Fig. 10. Type A dune-drift cross-laminations. Apparent current direction is from left to right.

base of the slip face (fig. 11).

No sinusoidal dune-laminations were observed.

In many cases it is impossible to distinguish between ripple drift and dune drift laminations when only lee side laminae are preserved. Extensive stoss side erosion of dunes may leave only low cross beds which one might interpret as type A ripple-drift laminae.

Antidunes

The structures preserved in the lower half of silt unit 18 appear to be antidunes (fig. 12). The cross-laminations are preserved as long, sweeping forsets with an apparent westward current direction. The forsets are inclined 5 to 10°, the crests are low and rounded. Antidunes do not exist as a continuous train of waves that never change, but waves that gradually build up with time from a plane bed and plane water surface. The water surface may build in height until they become unstable and break or they may gradually subside. When antidunes break, bed material is thrown into suspension. When antidunes do not break, the concentration of the bed material is only slightly higher than for the plane bed (continuous horizontal laminae) (Simons, et.al., 1965).

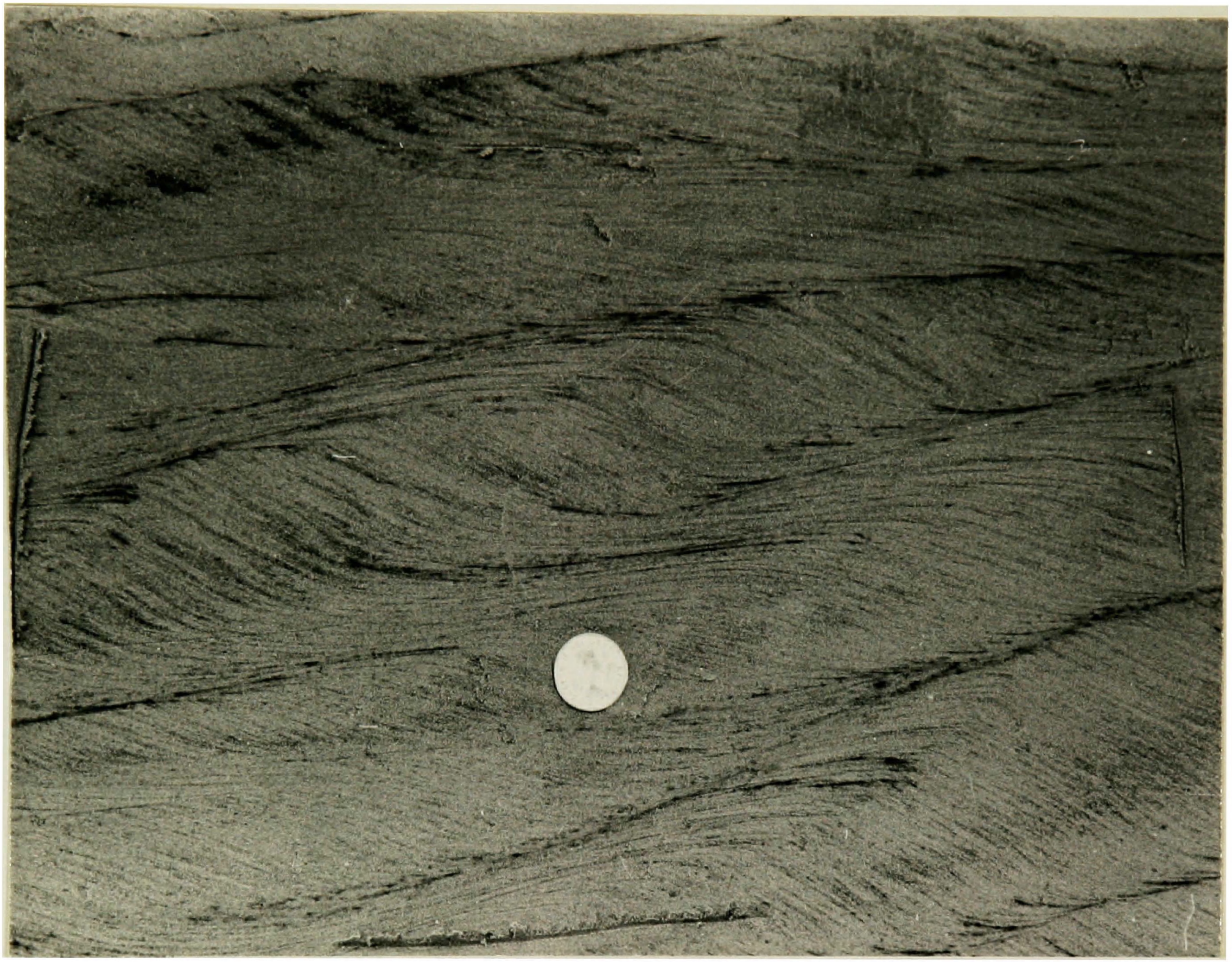


Fig. 11. Type B dune-drift cross-laminations. Apparent current direction is from left to right. Dime for scale.

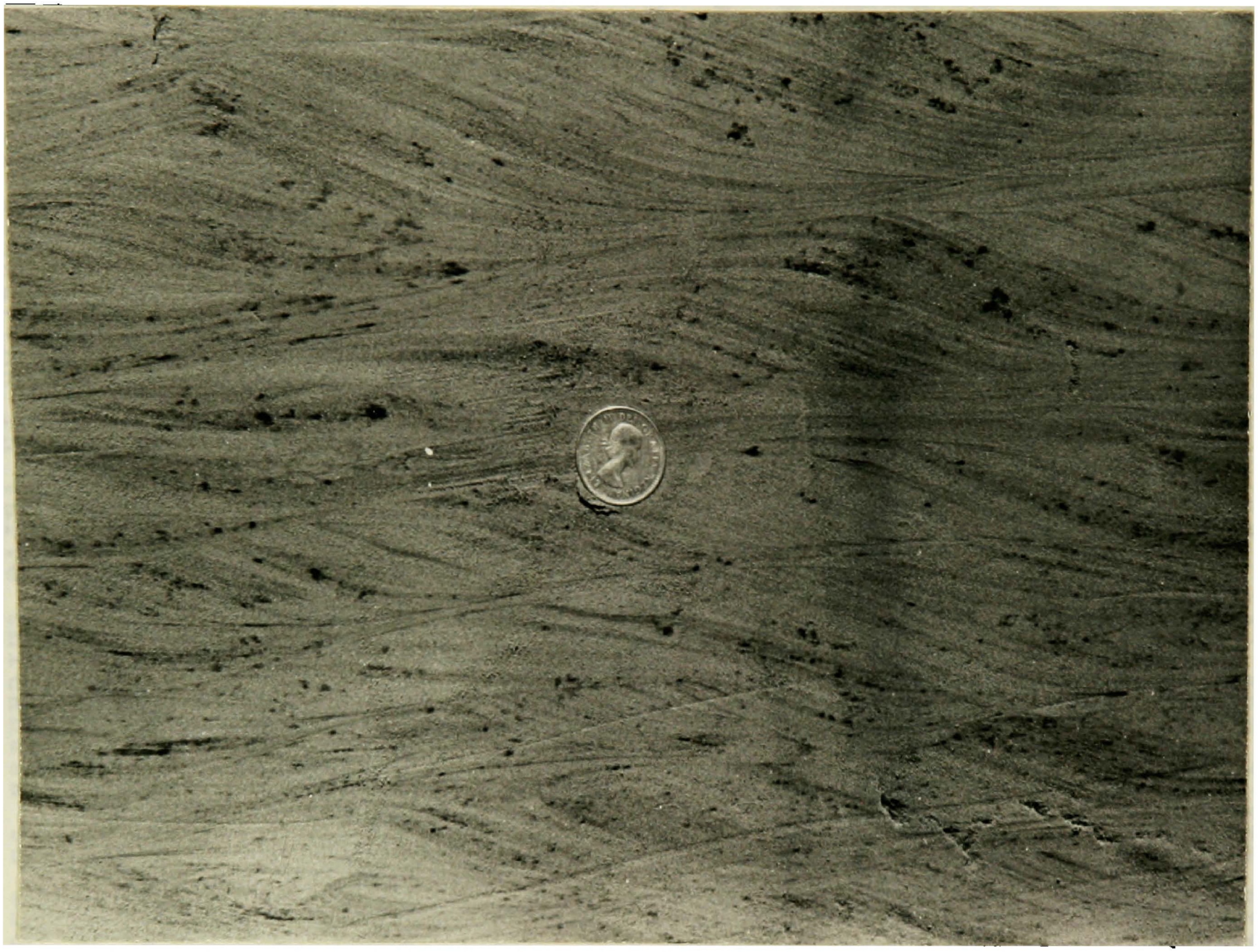


Fig. 12. Antidunes in silt layer 18 at locality SP. Apparent current direction is from right to left. Dime for scale.

Soft Sediment Deformation

Curl flow structures (fig. 13) and flame structures (fig. 14) frequently occur in the basal part of the silt layers. In every case the apparent current direction is westward. Curl structures (Arlee outcrop only) commonly form when influxes of fine sand overrides a layer of silt. Deformation occurs when the bed-load traction is great enough to roll the silt into the sand.

Flame structures result from bed-load traction of a lesser degree (fig. 14). The lower silt is displaced down current in the form of plumes, but not rolled as in the case of curl structures.

Varve Sequences

While measuring the sedimentary units, I observed a very consistent pattern in the varve sequences. In every case, the basal varves are much thicker than those near the top of any single sequence. The varves tend to thin progressively upward, until near the top of the sequence they are approximately 1 cm in thickness (fig. 15). I interpret the gradation in varve thickness to indicate that during the initial filling stages of the lake, the depositional basin was small and the varves produced were thick. With increasing water depth increasing the depositional basin area, the varves produced were thinner. As

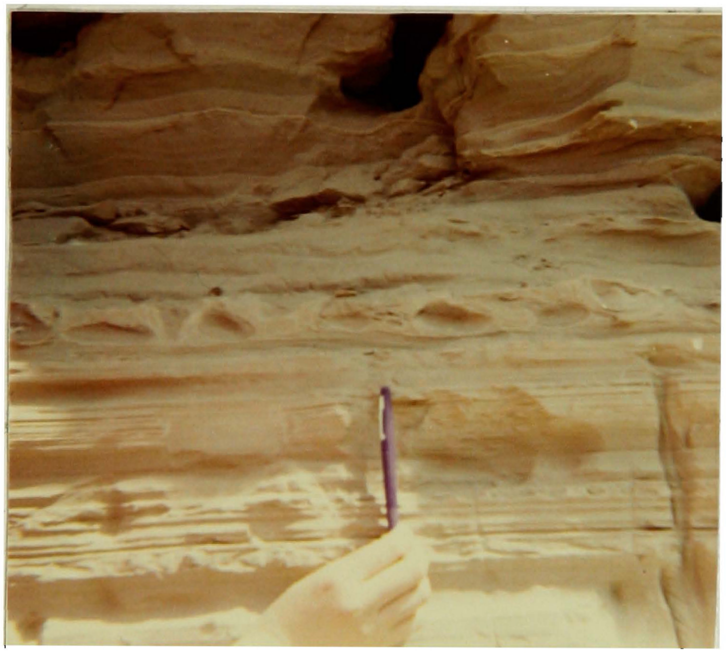


Fig. 13. Curl flow structures at locality JV. Apparent current direction from right to left.

Fig. 14. Flame structures in silt unit 9 at locality SP. Apparent current direction is from right to left.

Fig. 15. Trend in varves in unit 7 at locality SP.

the water depth stabilized, varves of nearly equal thickness were formed. Of course, this assumes that the sediment supply did not vary greatly from year to year.

The top 5 to 7 cm of 21 varve sequences appear to have been mechanically weathered by frost action and possibly by desiccation (fig. 16). The sediments have a dry, crumbly texture and are stained reddish orange by iron oxide. Because of the texture of these zones it is impossible to distinguish mud cracks, if present, from small scale frost cracks. It is impossible to count the number of varves in the weathered zones.

It is popular belief that mud cracks in sediments have been formed entirely by drying: the sediments are first deposited in water, and then either by draining or evaporation of the water, cracking develops upon exposure to the atmosphere. Although most mud cracks form this way, some have been observed to form under subaqueous conditions and are called synaeresis cracks (White, 1961).

Synaeresis cracks develop as fissures after the water is expelled from the clay-water system by internal forces; these may resemble mud cracks in sediments (White, 1961). These cracks form in clastic deposits containing greater than 70 per cent montmorillonite, where salt solutions form large clay floccules that settle slowly (Burst, 1965; White, 1961).

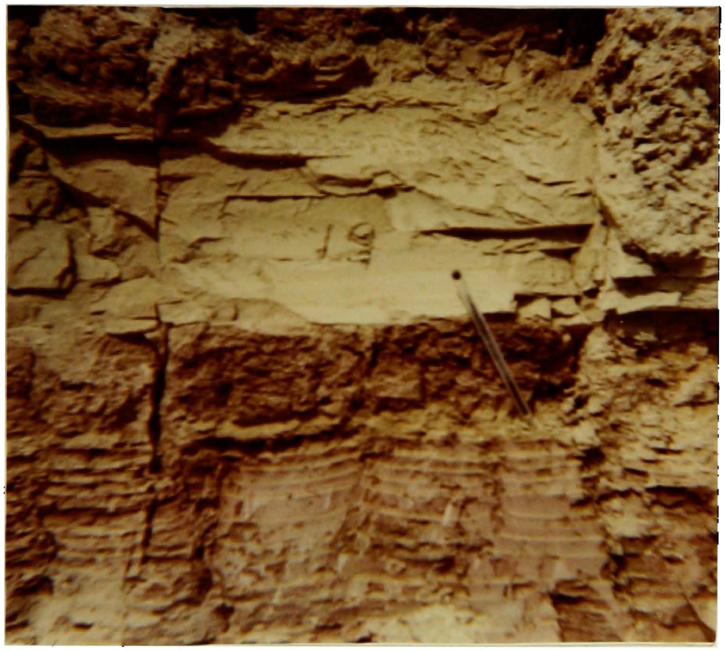


Fig. 16. Weathered zone in varve sequence 18 at locality SP.

I believe the Lake Missoula cracks are not synaeresis cracks because: 1) synaeresis cracks form only in highly saline solutions (2N), and 2) they form by flocculation of clay which is more than 70 per cent montmorillonite. Obviously, Glacial Lake Missoula was not saline and Sieja (1959) found twice as much illite as montmorillonite.

Flint (1957) believes that varves form only in cold lake water with a moderate amount of circulation, and when electrolytes are absent, which tend to flocculate the clay suspensions.

The frost wedges in the weathered zones are about 10 to 12 inches long, an inch or more wide at the top, tapering to the base (fig. 17). These cracks, in contrast to mud cracks, tend to curve upward slightly at the base. The frost wedges are held open by infilling of weathered varve material. The presence of frost wedges strongly indicates periglacial conditions at this time in the lake's history. I believe that most of the mechanical weathering of the varves was due primarily to frost action, although some desiccation of the sediments may have occurred also.

Small lenses of festoon, cross-bedded sands and gravels were noted at the top of some varve sequences (fig. 18). The gravels are imbricated and suggest a westward current direction. The sand and gravel was apparently deposited by small streams flowing down the adjacent hill-

Fig. 17. Frost wedge in unit 18 at locality SP.

Fig. 18. Festoon cross-bedded sands and gravels at locality SP.

sides across the drained lake floor. The gravel is slightly cemented by calcium carbonate and stained by iron oxide before burial by the overlying unit. Apparently the water flowing in these small channels was of short duration.

I suggest that each of the stratigraphic units represents a lake level fluctuation and that mud cracks, frost wedges, frost cracking, and oxidized zones are indicative of times in which the lake sediments were exposed to the atmosphere.

Geologic Environment of the Silt Layers and Varve Sequences

While the varves were exposed to subaerial weathering, glacial meltwater streams flowed across the extensive, flat lake bottom. After the ice dam formed downstream, the water slowly backed up until the area became flooded. The streams flowing into the rising lake were probably rather shallow and carried a large amount of bed-load and suspended-load sediment. Also, the transition from a fluvial to lacustrine environment was probably rather gradual because of the gently sloping lake floor. It is impossible to distinguish between topset, foreset, and bottom set beds in the silt layers (fig. 19).

For a glacial lake environment characterized by the

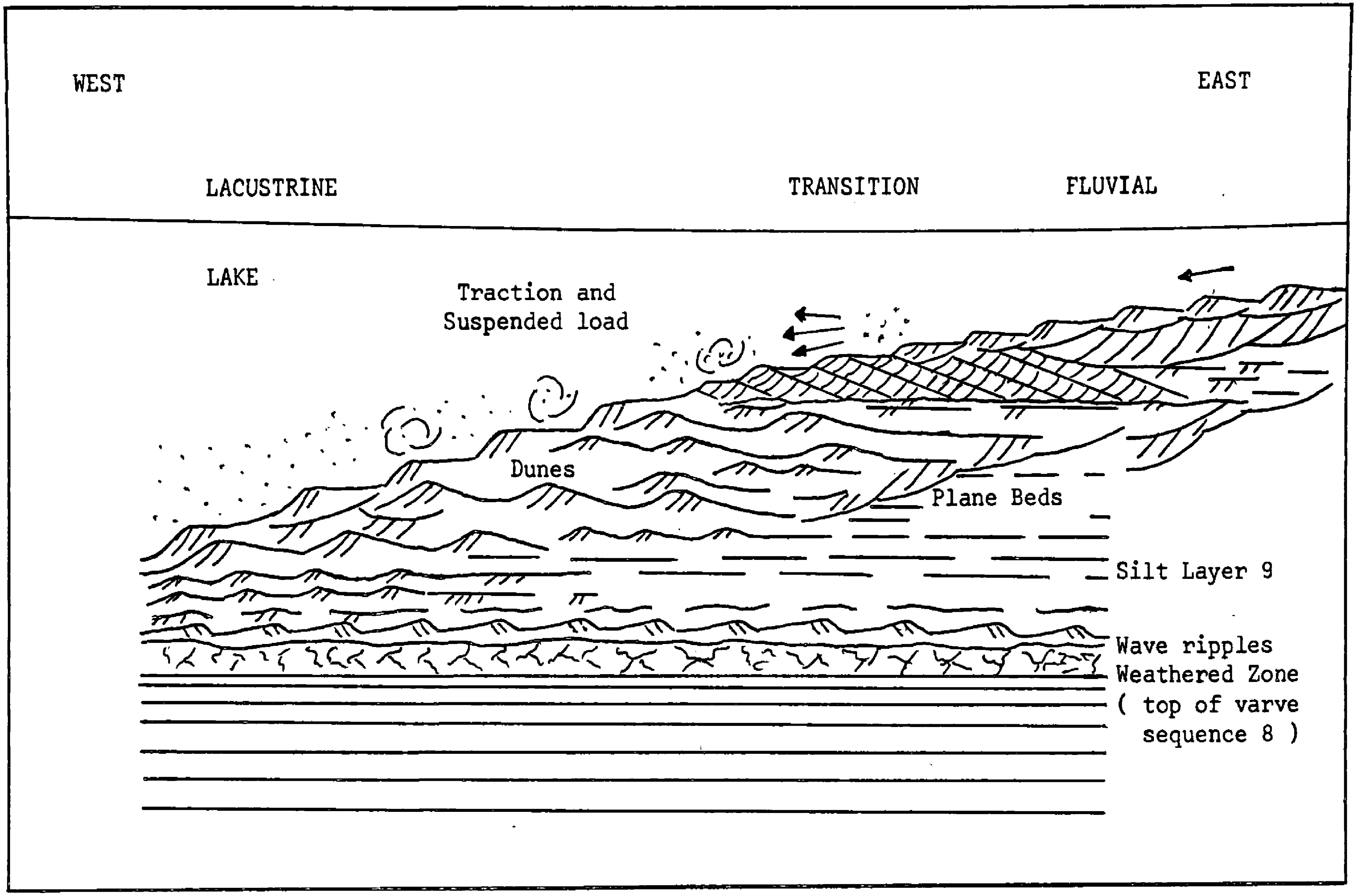


Fig. 19. Diagrammatic representation of the environmental conditions of deposition in Glacial Lake Missoula. Vertical scale greatly exaggerated.

influx of sediment laden water, it seems reasonable to suggest deposition from density underflows into the lake basin. Most of the silt layers consist of continuous horizontal laminations (planar beds) which suggest deposition of sediment during transitional flow in rather shallow water. Silt layers 9,13,18, and 22 at locality SP contain the various types of sedimentary structures mentioned in the preceding pages. Type A ripple-drift and dune-drift cross-laminations (figs. 6 and 10) demonstrate the importance of traction-load movement. Examination of the sinusoidal ripple laminations (fig. 7) and type B ripple-drift and dune-drift cross-laminations (figs. 6 and 11) demonstrate the importance of a high rate of deposition from suspension. Because of the very intimate association of the various sedimentary structures in several of the silt layers, it seems reasonable that small changes in the hydrodynamic environment will modify significantly the aspect of sedimentary structures that are formed, according to Jopling and Walker (1968). They also state that small variations in composition, concentration, and rate of deposition of the sediment, and depth of flow, and water velocity are the primary factors controlling the different types of sedimentary structures.

The lack of scouring within any silt layer suggests that deposition resulted from a more or less continuous, although slightly pulsating, density underflow, rather than by turbidity currents. Jopling and Walker (1968) pointed out that in turbidity currents, the gradual upward decrease in amplitude and overall graded bedding indicates deceleration of the current during deposition. There is also an upward change from slightly eroded stoss side to fully preserved stoss side ripple and dune laminae; the planar beds are formed by deposition from suspension, indicating a gradual increase in the suspension/traction ratio. No graded bedding nor upward decreases in amplitude of sedimentary structures were observed in the Lake Missoula sediments. All of the sedimentary structures, except the wave ripples, suggest a westward current direction in all outcrops. This enigma will be explained on the next page.

My interpretation is based on the idea of a gently sloping lake floor traversed by gentle currents carrying fine sand and silt, with "deltas" retrograding eastward.

Jopling and Walker (1968) described a kame delta which has sedimentary structures similar to those observed in the silt layers of the Lake Missoula deposits. The delta they described, however, has topset, foreset, and bottomset beds. They interpreted that density underflows built a delta which prograded into a standing body of water.

During the initial rising water stages in Lake

Missoula, the entire lake bottom was probably not flooded (fig. 20). With rising lake water to the west, and formation of the delta, the exposed lake sediments were being eroded to the east. Evidence for erosion of the lake sediments is indicated by the presence of rounded, varved clasts in two silt layers.

The initial water depth to the west was probably rather shallow as indicated by the preservation of asymmetrical wave ripples. These features were probably formed by breaking waves, eastward transport of sediment, accompanied by rapid burial, resulting from prevailing westerly winds. The wave fetch across the Missoula Valley is quite extensive and the waves were probably large enough to transport the incoming silt. The prominent shorelines on Mt. Jumbo and University Mountain, west-facing hill slopes, are another indication of strong prevailing westerly winds. With increasing water depth and decreasing water agitation varves may begin to form, with subsequent migration of the "delta" upstream (fig. 21). This process would continue until the entire basin was flooded and varve deposition was continuous over the lake basin.

As noted earlier, the varves are thickest near the base of any single varve sequence and thin progressively upward. The basal varves to the east probably overstep the silt layers to the west (fig. 22). The varves could

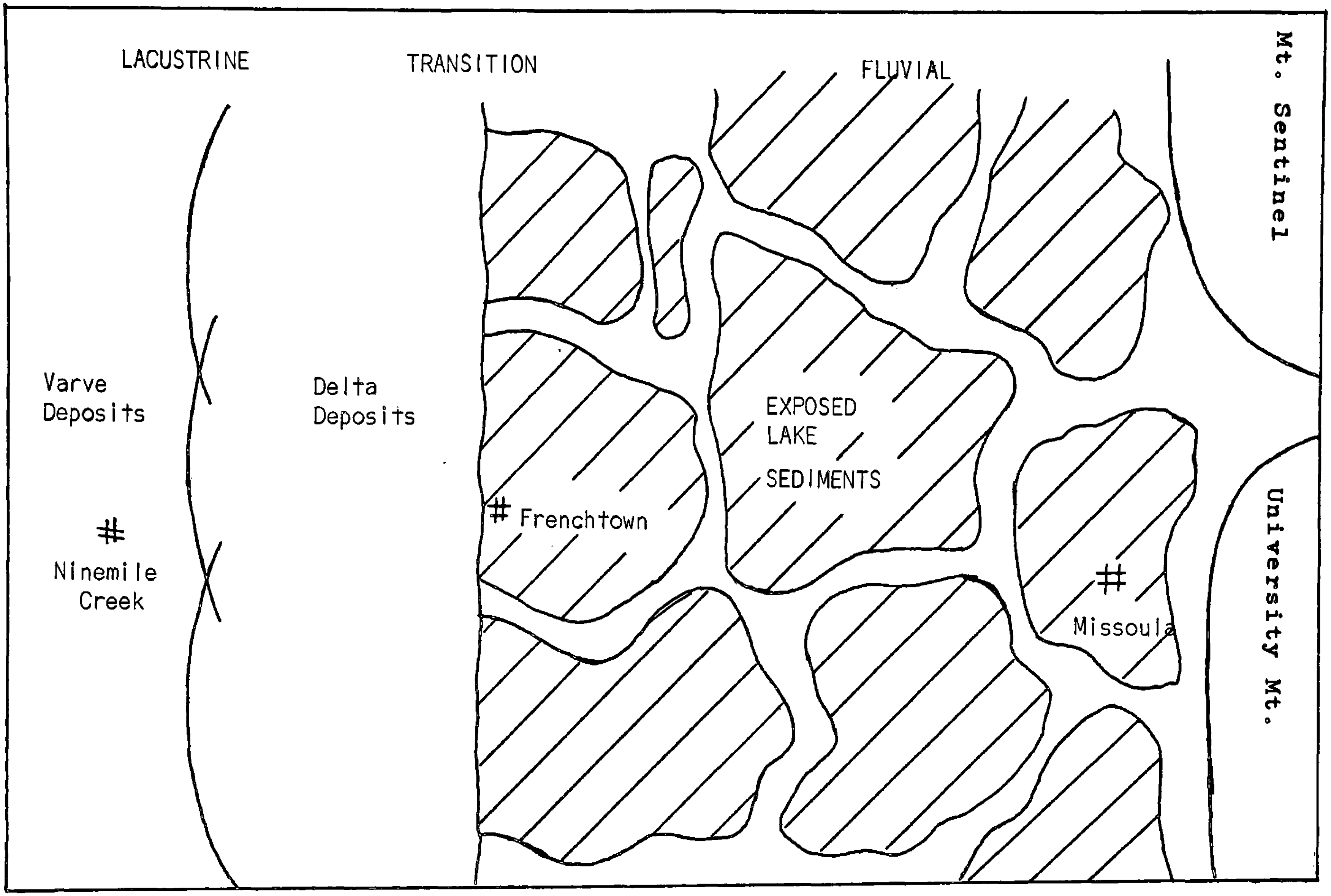


Fig. 20. Early flooding stage of the Missoula Valley.

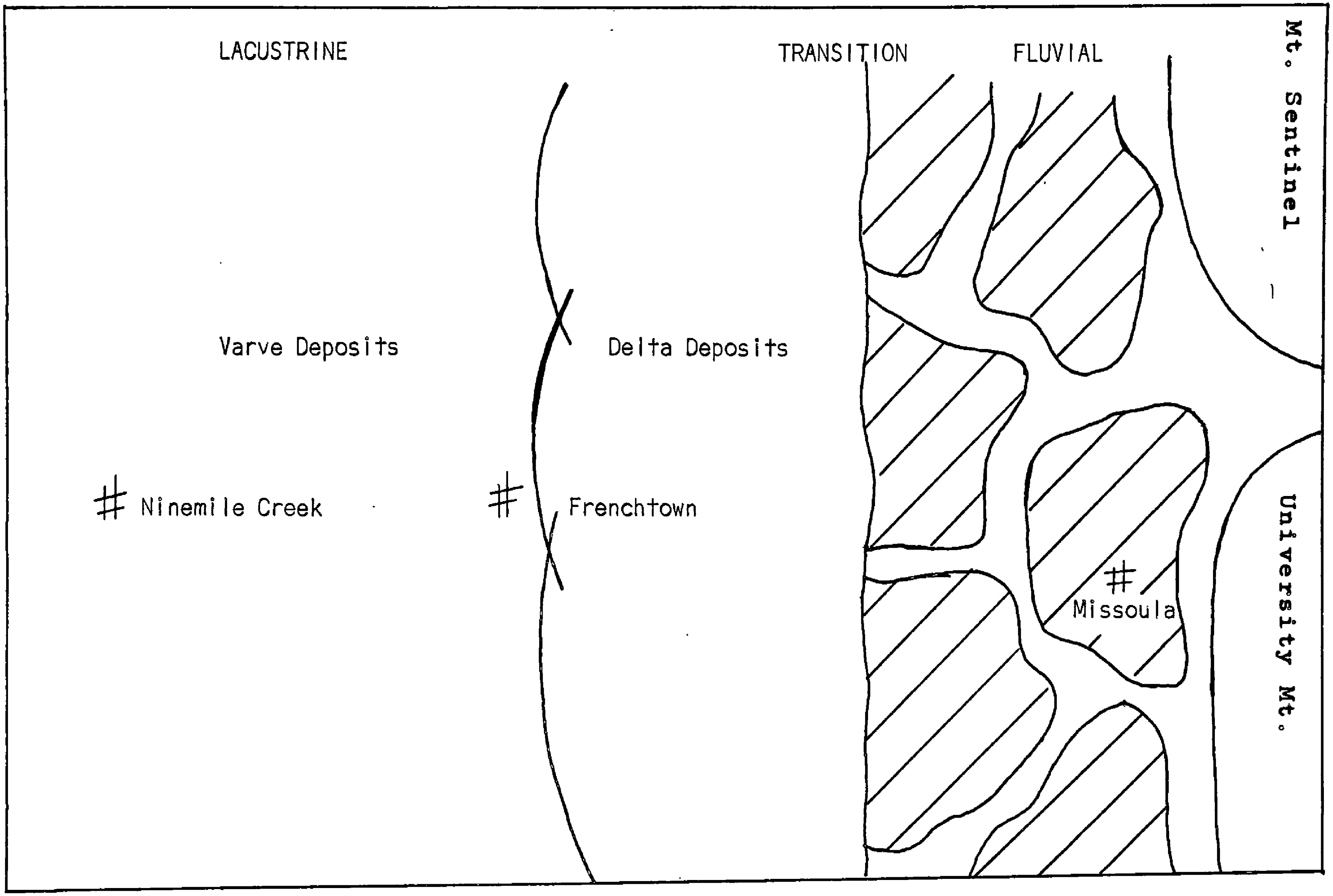


Fig. 21. Later flooding stage of the Missoula Valley.

not be correlated because the outcrops are too widely separated. Sieja (1959) could not correlate outcrops more than 75 yards apart. One silt layer traces for more than two miles. It pinches out to the west and thickens eastward, which for the Missoula-Ninemile basin suggests a source area probably from the mouth of the Hellgate Canyon.

The number of varves in any sequence represents the minimum number of years between lake level fluctuations. The height to which the lake level rose is probably directly related to the number of years it filled, and the years can be determined by the number of varves. The water depth was probably not the same each time, and was probably never very deep during the mid to late Pinedale period.

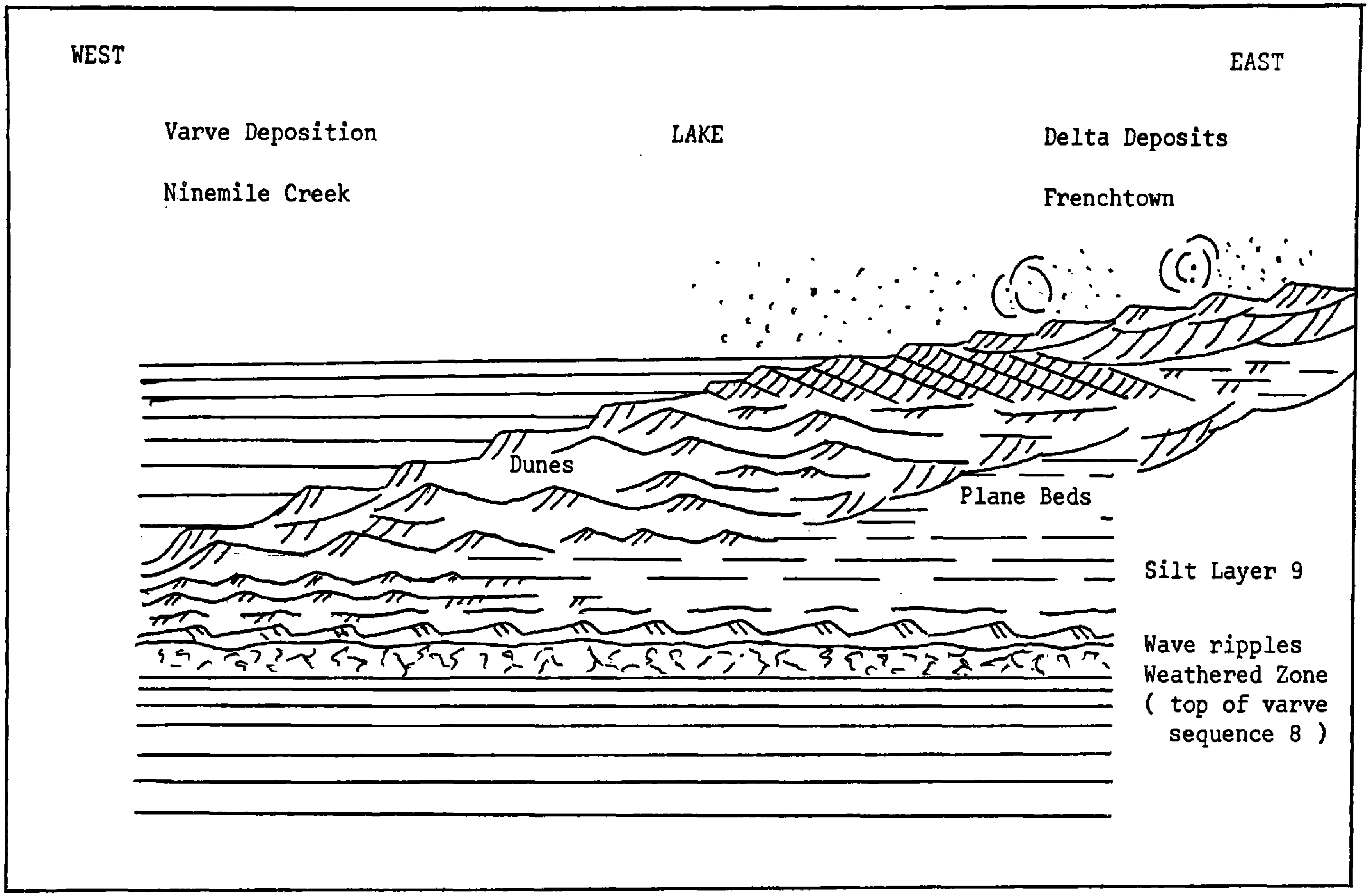


Fig. 22. Diagrammatic cross-section of varve and delta deposition from Nine mile Creek to Frenchtown. Note that the varves overstep the delta deposits to the east, Vertical scale greatly exaggereated.

CHAPTER 4

SOIL HORIZONS

The giant current ripples at Camas Prairie, described by Pardee (1942) are overlain, in part, by varved lake sediments. A soil has developed on both the lake sediments and gravel deposits, however, there is no buried soil between them (fig. 23). Fossil plants (grasses?) occur at the top of the gravels, suggesting a short period of subaerial exposure before resubmergence of the gravels and deposition of the lake sediments. The soil, based on its weak A/C profile, suggests no more than 15,000 years time after the last lake draining (R.R. Curry, letter to Dr. William Bradley, University of Colorado, 1970). Fryxell and Daughtery (1962, 1968; from Bretz, 1969) dated the last Cheney-Palouse discharge, in eastern Washington, at about 12,000 years B.P.

The current ripples at Camas Prairie show at least two sequences of gravel deposition, separated by a buried and dismembered carbonate soil horizon (figs. 24 and 25). The carbonate horizon is a 6 to 10 inch hardpan suggesting that the dunes were stable and subaerial for a long period of time. No hardpan has formed in the late glacial and modern soil in the upper gravel sequence.

Another hardpan, similar to that at Camas Prairie, was recognized in a mudflow about 7 miles north of Arlee along

Fig. 23. Lake deposits overlying flood gravels at Camas Prairie

Fig. 24. Torn apart k-horizon (underlined) in flood gravels at Camas Prairie.

Fig. 25. Closeup of K-horizon in figure 24.

Highway 93 on the north side of the road. The mudflow is overlain by 17 Glacial Lake Missoula sedimentary units and 308 varves were counted here (fig. 26). The mudflow also has a moderately well developed B and C horizon with a total depth of oxidation about 5 feet (figs. 27). The hardpan in this outcrop appears, by comparative development, to be the time equivalent of the hardpan formed in the dunes at Camas Prairie, however, radiometric dates are needed to confirm this hypothesis (fig. 28).

The hardpans mentioned above are accumulations of authigenic carbonate which commonly form the dominant soil horizon in arid regions; the morphology of the soil being determined by the impregnating carbonate. These soils form in a time related sequence; the amount of carbonate accumulation increases markedly with increasing time of subaerial exposure in arid regions (Gile, et.al., 1965).

Definition of the K-horizon

Gile, et.al. (1965) have proposed a new master horizon termed the K-horizon, to meet the need for nomenclature and notation for soils with prominent carbonate accumulation. This horizon also has a diagnostic K-fabric.

The K-fabric is a fine-grained authigenic carbonate and occurs as a continuous medium. It engulfs and commonly separates the cemented grains. The juncture of the carbo-

Fig. 26. Lake sediments overlying mudflow and channel fill at locality JV.

Fig. 27. B and C horizons in the mudflow at locality JV. Total depth of oxidation is about 6 feet.

Fig. 28. Closeup of K-horizon in figure 27.

nate coatings can be missing at a few contact points without negating the essential continuity of the carbonate matrix. Because of mineralogical differences, the boundary between the allogenic grains and authigenic carbonate matrix is obvious. The carbonates are usually light colored and have consistencies ranging from soft to extremely hard and may be indurated. The material breaks down completely under HCl treatment. The K-fabric has widely varied microscopic forms, such as massive, platy, blocky, nodular, or laminar (Gile, et.al.,1965). Laminar and massive, nodular forms are illustrated (figs. 29 and 30). A minimum range from 15 to 40 per cent authigenic carbontate is required for the formation of the K-fabric, anything less is termed a caliche (Cca) (Gile, et.al., 1965).

The K-horizon is divided into three subhorizons; 1) the K1 has 50 per cent or more by volume K-fabric, and is transitional from the overlying B horizon; 2) K2 horizons have 90 per cent or more by volume K-fabric, and is designated K2m if indurated. The K2 horizon is transitional from the K1 horizon; 3) K3 horizons are transitional from the K2 or K2m horizons to the underlying Cca horizon. The K2 horizon is the most prominent, hardest part of the K-horizon (Gile, et.al., 1965). K-horizons form in a series of stages and are summarized in Table 6.

Fig. 29. Laminar K-horizon.

Fig. 30. Massive, pebble-studded K-horizon from Camas Prairie.

Stage	Diagnostic Carbonate Morphology	Youngest geomorphic surface on which stage of horizon occurs
I	Thin, discontinuous pebble coatings	Fillmore (local) 2600 to 4990 years B.P.
II	Continuous pebble coatings, some interpebble fillings	Leasburg (local) 4990 to 9550 years B.P.
III	Many interpebble fillings	Picacho (local) 9550 years B,P, to late Wisconsin
IV	Laminar horizon overlying plugged horizon (thickened laminar and plugged horizons)	Picacho (local) pre-late Wisconsin to post late Kansan-Illinoian

Table 6. Stages and Morphologenetic Sequences of Soil Horizons and the youngest land surface on which they appear (after Gile, et. al., 1966; Ruhe, 1967).

Age Estimations of the K-horizon and Stratigraphic Units

Pardee (1942) has shown that the giant current ripples at Camas Prairie, were the result of catastrophic flood waters. These features could only form when water spilled from the Little Bitterroot Valley over Markle Pass and Will's Creek Pass.

I recognize two flood sequences at Camas Prairie separated by a fragmented K-horizon (fig. 31). This is not to say, however, that only two flood periods occured. Each new flood probably reworked the older deposits forming a new set of ripples. The upper gravel sequence is characterized by stages I and II authigenic carbonate accumulation, while only broken pieces of stages III and IV have been preserved as lag deposits at the top of the lower gravel sequence.

Gile, et.al.(1965) and Ruhe (1967) have shown that K-horizons (stages III and IV) need at least 9550 plus years to form (table 6). However, no modern K-horizon has formed in the modern soils of the upper gravel sequence, which may be 15,000 years old. The soils reported on by Gile, et.al. and Ruhe are now forming in southern New Mexico and are probably forming faster than those at Camas Prairie and Arlee.

I suggest that the lower gravel sequence formed by

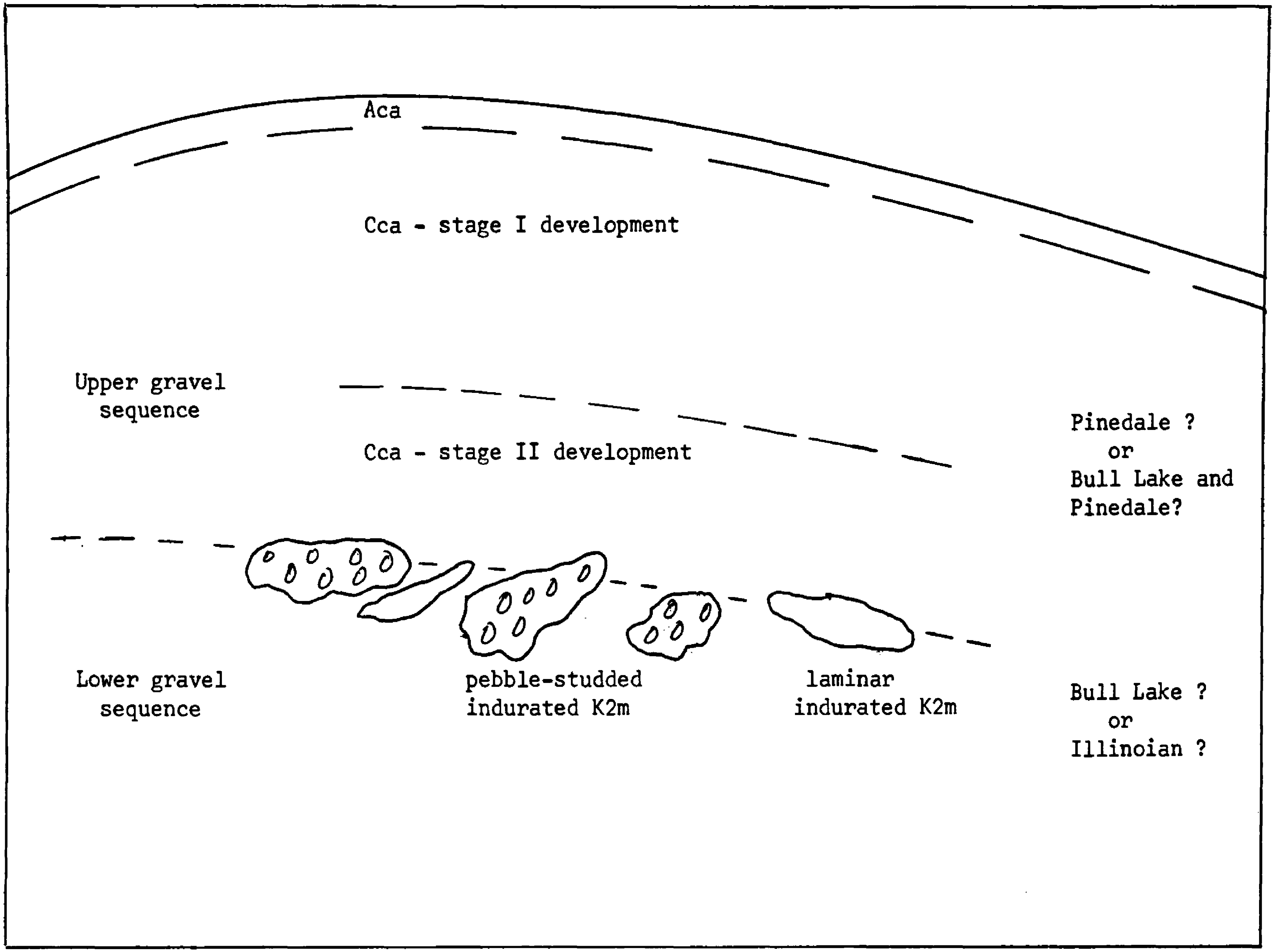


Fig. 31. Diagrammatic cross-section of the flood deposits at Camas Prairie.

catastrophic flood waters during late Bull Lake time (32,000 years B.P., after Richmond, 1965), followed by an early Pinedale flood (20,000 years B.P., after Richmond, 1965), separated by the fragments of the K-horizon. This would place the age of the K-horizon in the 12,000 year long Bull Lake-Pinedale interstadial. However, the 12,000 years alloted, by Richmond, for the interstadial does not seem to be a sufficient amount of time to develop a mature K-horizon. Possibly the interstadial had a warmer, drier climate which favored the formation of a K-horizon. According to Robert Curry (personal communication, 1971) Richmond's figures may be inaccurate by several thousands of years and the duration of the interstadial period may be closer to 23,000 years. An additional 11,000 years of warmer, drier climates may be long enough to produce a K-horizon. The varved lake deposits overlie all earlier flood deposits and are interpreted as being solely mid to late Pinedale in age.

Richmond and others (1965) have evidence for what they believe to be the occurence of a flood at the close of the pre-Wisconsin glaciation. This could place the lower gravel sequence as late Illinoian in age (405,000 years B.P.) and formation of the K-horizon during the 300,000 year-long Sangamon interglacial. The upper gravel sequence and lake sediment would then be Bull Lake and Pinedale in age. This interpretation seems unlikely for most students of Lake

Missoula believe that nearly all the flood deposits are Bull Lake, or at least Wisconsin in age (Bretz, 1969; Bretz, et.al., 1956; Pardee, 1942). I tend to favor the Bull Lake-Pinedale hypothesis.

My interpretations on the ages of the soils are purely speculative without radiometric dates to confirm my hypotheses.

CHAPTER 5

CHRONOLOGIC SUMMARY OF EVENTS DURING THE LATE PLEISTOCENE IN WESTERN MONTANA

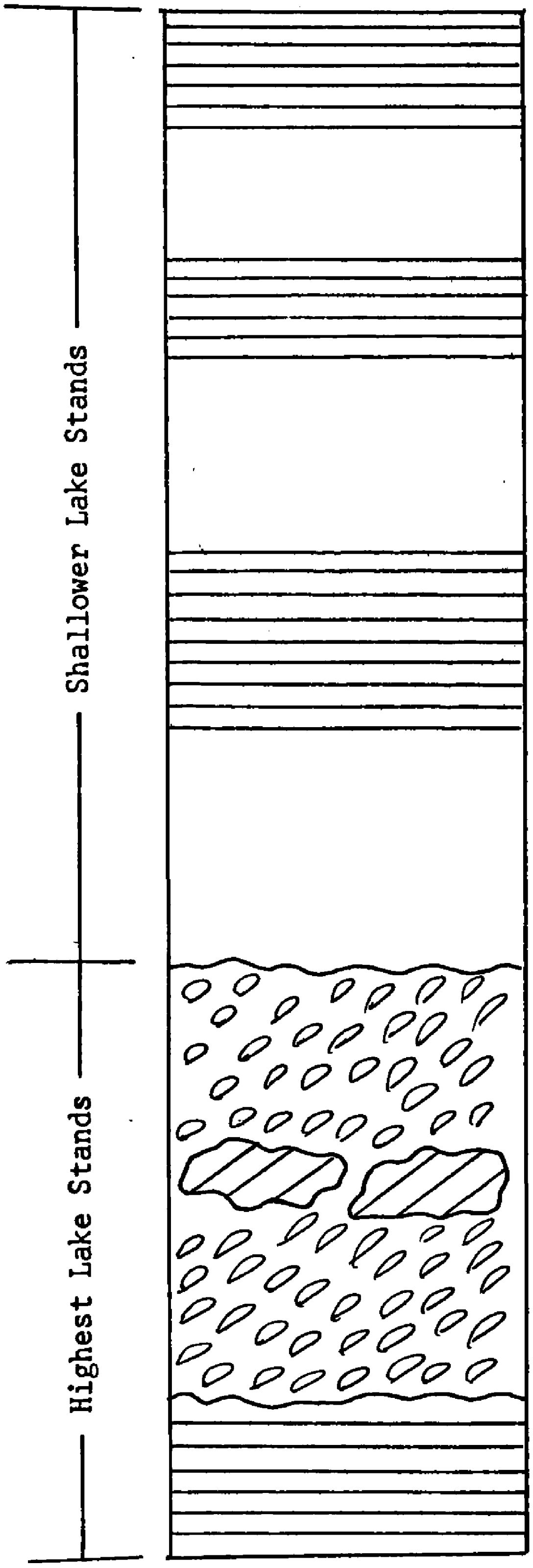
At times of glacial maximum a lobe of ice flowing down the Purcell Trench dammed the Clark Fork River drainage, at Pend Oreille, Idaho, forming Lake Missoula. The lake occupied six major intermontane basins in western Montana (fig. 1). Upon failure of the ice dam, catastrophic flood waters swept across northern Idaho and eastern Washington forming the Channeled Scablands.

The highest lake stands probably occurred during the late Bull Lake and early Pinedale Glaciations when the Flathead Lobe occupied the major portion of the Mission Valley.

The giant current ripples at Camas Prairie (Pardee, 1942) record catastrophic flood waters pouring over Markle Pass and Will's Creek Pass. I recognize two flood gravel sequences separated by a buried and dismembered K-horizon. The two gravel sequences represent what I believe to be evidence for a late Bull Lake flood, followed by a second flood during the early Pinedale. I interpret the K-horizon as having formed during the Bull Lake-Pinedale interstadial. It is possible that 20,000 years is not a sufficient amount of time to form a K-horizon and it may have formed during the Illinoian-Wisconsin Sangamon interglacial which lasted 300,000 years. However, I favor the Bull Lake-Pinedale hypothesis.

The Polson terminal moraine marks the farthest advance of the Flathead Lobe during late Pinedale (Richmond's middle Pinedale, table 1, p. 10). The major portion of the Mission Valley was now free to hold water and the lake was only filled to low elevations. Most of the older, higher shorelines developed patterned ground, formed during periglacial conditions (R.R. Curry, oral communication, 1971).

Forty stratigraphic units were recognized at locality SP and interpreted as being late pinedale in age. Figure 32 represents a chronologic summary of events during the late Pleistocene history of Lake Missoula.



Forty stratigraphic units deposited during late Pinedale time. Each unit represents a partial refilling of the lake (locality SP).

Varve Sequence

Silt Layer

Plant fossils (Camas Prairie).

Flood gravels; early Pinedale (20,000 years B.P.) (Camas Prairie).

K-horizon; Bull Lake-Pinedale interstadial (Camas Prairie).

Flood gravels; late Bull Lake (32,000 years B.P.) (Camas Prairie).

Bull Lake age varves recognized by Richmond, et, al., 1965; however not observed by the present writer,

Fig. 32. Diagrammatic, composite chronologic sequence of events during the late Pleistocene history of Glacial Lake Missoula,

APPENDIX I

METHODS OF INVESTIGATION

The usual procedure for collecting field data was to prepare a series of steps up the roadcuts shaping smooth vertical faces on each rise. The actual thicknesses of the varves were recorded directly from the exposure onto a roll of adding machine paper. Samples for X-ray and carbonate analysis were collected approximately every six inches, stored in plastic bags, and sealed in cardboard containers. Approximately thirty days were spent in the field collecting data. About a dozen scattered outcrops were studied (fig. 1), however, only three were carefully measured (see Appendix III).

X-Ray Diffraction Procedure

The purpose of the X-ray study was to determine whether the clay minerals changed through a vertical section. Each sample was size cut to obtain fractions of less than one micron equivalent settling diameter. Suspensions of clay-size material were centrifuged onto unglazed porcelain plates in order to obtain maximum orientation parallel to the basal plane (Kinter and Diamond, 1956). The samples were treated with ethylene glycol.

One sample was also treated with potassium hydroxide to test for the presence of vermiculite. The sample was soaked in 2N KOH for forty-eight hours, washed with distilled water, treated with ethylene glycol, and X-rayed. Sieja's method (1959, p. 42) for KOH treatment was followed.

X-ray patterns were obtained with a Norelco scanning X-ray diffractometer, utilizing CuK alpha radiation.

Calcium Carbonate Analysis

Several grams of each sample were oven dried for 2 hours at 200°C. The sample was cooled, weighed and treated with 1N HCl until no further action was noted. The sample was washed with distilled water, oven dried for 3 hours at 200°C, cooled, and reweighed. The loss in weight was ascribed to calcium carbonate (table 3).

APPENDIX II

The Problems of Lake Drainages

The following pages are presented in order to illustrate some of the problems and possible mechanisms relating to the drainage of glacially ice-dammed lakes.

It has already been noted that Lake Missoula occupied the main valleys in western Montana and was dammed by ice in the lateral valley of the Purcell Trench. Lake George, the largest existing glacial lake in Alaska occupies a lateral valley and is dammed by ice in a main valley. In 1963, there were more than 52 other ice dammed lakes in Alaska and in the adjacent area of British Columbia. All of these lakes drain under or through the ice. No instances of water overtopping the ice have been recorded (Embleton and King, 1968).

All observers agree that the usual method of glacial drainage is subglacially or englacially. Supraglacial drainage is rare, except in cases where sub-zero ice temperatures preclude subglacial or englacial routes (Embleton and King, 1968).

There is considerable controversy over the mechanism by which lakes drain subglacially, especially with respect to sudden bursts. The water will undoubtedly find its way into crevasses, into gaps between the ice and bedrock, and may travel for a considerable distance beneath the ice. The major problem is how subglacial outlets are first opened and how they remain open until the lake has emptied or at least partially emptied.

S. Thorarinsson (1939) has suggested that subglacial drainage is initiated by floating the ice dam, after a critical water level is reached. The critical level is about nine-tenths the height of the ice barrier. The problem of how to overcome the contact between the ice and the bedrock also arrises; especially if the ice is frozen to the bedrock. J.W. Glenn (1954) has suggested, from experiments on mechanical properties of ice, that drainage may start when the water resting against the ice dam exerts a stress sufficient to deform the ice at the base of the water mass. These two mechanisms may cause only intermittent outflow and not a sudden rush, especially if the barrier is not eroded and broken up.

The movement of a glacier over an irregular surface will open cavities under the ice large enough to allow water to penetrate and start drainage from the lake. After water begins to flow, the passage will be kept open and enlarged by melting as a result of heat surplus if the temperature of the water is above 0°C (Liestøl, 1956, pp. 123-125). After the ice barrier has been lifted by floation and the lake level has dropped, the ice probably will not fall back into its former position; also icebergs wedged in the tunnels might help prevent collapse (Aitkenhead, 1960).

Liestøl's and Aitkenhead's suggestion for the maintenance and enlargement of tunnels to allow for complete lake draining in one burst are reasonable additions to Thorarinsson's and Glenn's hypothesis.

APPENDIX III

The section described below is the reference section of the Pinedale age equivalent (?) sediments. Locality SP is exposed as a large road cut on U.S. Highway 10 immediately east of the bridge over the Clark Fork River at Ninemile Creek and approximately six miles west of Frenchtown, Montana. Approximately 80 feet of sediments are exposed. In all cases, the basal varves are thicker and thin progressively upward in any single varve sequence. All measurements are in centimeters.

Units 34-40 were not measured because of deep mechanical weathering. An estimation of 75 to 100 varves was made. A total of 716 varves were measured in this outcrop.

Unit	Description	Silt thickness	Unit thickness	Cumulative thickness
33 -	The silt has continuous horizontal laminations. No varve count possible because of deep mechanical weathering.	3.8	-	235.7
32 -	The silt layer consists of continuous horizontal laminations overlain by 12 varves averaging 0.98 cm.	5.3	17.0	2347.9
31 -	The silt layer consists of continuous horizontal laminations overlain by 20 varves averaging 1.27 cm.	7.9	33.3	2330.9

Unit	Description (cont.)	S.T.	U.T.	C.T.
30 -	The silt layer consists of continuous horizontal laminations overlain by 12 varves averaging 1.45 cm.	7.1	24.5	2297.6
29 -	The silt layer consists of continuous horizontal laminations overlain by 9 varves averaging 1.86 cm.	9.0	25.5	2273.1
28 -	The silt layer consists of continuous horizontal laminations overlain by 19 varves averaging 1.0 cm. There is a small festooned sand and gravel layer at the top of this sequence, which is also weathered and iron stained.	13.0	32.0	2247.6
27 -	The silt consists entirely of continuous horizontal laminations overlain by 17 varves averaging 1.47 cm. The top 9.7 cm is weathered and iron stained	16.5	50.9	2215.6
26 -	Small scale wave ripples are preserved in the basal silt, overlain by continuous horizontal laminations. There are 10 varves averaging 1.89 cm. The top 5.7 cm is weathered and iron stained.	32.9	57.5	2164.7
25 -	The basal silt has small scale wave ripples preserved overlain by continuous horizontal laminations. There are 22 varves averaging 1.24 cm. The top 2.3 cm is weathered and iron stained.	23.6	53.3	2107.2

Unit	Description (cont.)	S.T.	U.T.	C.T.
24 -	The silt has continuous horizontal laminations overlain by 17 varves averaging 1.72 cm. The top 3.5 cm is weathered and iron stained.	33.6	67.3	2053.9
23 -	The silt has continuous horizontal laminations overlain by 25 varves averaging 1.25 cm. The top 4 cm is weathered and iron stained.	16.5	51.6	1986.6
22 -	The basal 4 cm of silt has type A ripple laminae, these are overlain by type B dunes. The top 13 cm has continuous horizontal laminations. These 25 varves averaging 1.27 cm. The top 5 cm is weathered and iron stained.	113.3	150.1	1935.0
21 -	Small scale wave ripples are preserved in the basal silt, the rest of the silt has continuous horizontal laminations. There are 23 varves averaging 1.56 cm. The top 11.7 cm of this unit is very hard and dried out. This layer has large concentrations of $CaCO_3$ (see section concerning $CaCO_3$ analysis).	20.5	68.1	1784.9
20 -	The silt has continuous horizontal laminations overlain by 22 varves averaging 1.64 cm. The top 7.15cm of this unit is weathered and iron stained. Wave ripples are present at the base of the silt.	9.5	52.9	1716.8

Unit	Description (cont.)	S.T.	U.T.	C.T.
19 -	The silt has continuous horizontal laminations overlain by 25 varves averaging 1.23 cm. Wave ripples are present at the base of the silt.	29.4	60.2	1663.9
18 -	The silt layer is divided into two sublayers: 1) antidunes with long sweeping cosets, apparent current direction westward (32.3 cm), and 2) continuous horizontal laminations (67.5 cm). There are 58 varves averaging 1.36 cm. The top 8.7 cm is weathered and iron stained.	99.5	187.2	1603.7
17 -	Small scale wave ripples are preserved in the basal silt, the rest of the silt has continuous horizontal laminations. There are 27 varves averaging 1.17 cm. The top 7 cm of the varves are weathered and iron stained.	10.9	49.2	1416.5
16 -	The continuous horizontal laminations are broken 19 cm up by a 2 cm thick layer of rounded varve clasts. There are 33 varves averaging 1.49 cm. The top 5 cm is weathered and iron stained.	36.9	90.2	1367.3
15 -	The silt layer has continuous horizontal laminations overlain by 31 varves averaging 1.19 cm.	11.5	48.4	1277.1

Unit	Description (cont.)	S.T.	U.T.	C.T.
14 -	The silt layer has continuous horizontal laminations overlain by 29 varve averaging 1.43 cm. The top 18 cm of the varve sequence is weathered and has iron stains.	44.9	104.4	1228.7
13 -	The lower 7.5 cm of the silt layer has type B ripple-drift cross-laminations with an amplitude of 2.1 cm and a wave length of 13 cm. The last 8.2 cm has continuous horizontal laminations overlain by 35 varves averaging 1.15 cm. The top 7 cm of the varves is weathered and iron stained.	15.7	63.2	1123.3
12 -	The basal part of the silt has small scale wave ripple laminae which are overlain by continuous horizontal laminations. The entire varve sequence is weathered and has iron stains. No count of the varves was made.	7.3	18.5	1061.1
11 -	The silt layer has continuous horizontal laminations overlain by 33 varves averaging 1.41 cm.	17.6	63.9	1042.6
10 -	The basal 47 cm of silt has continuous horizontal laminations. These laminations are broken by a 5 cm layer containing rounded clasts of varves sediments, which is overlain by more continuous horizontal laminations. There are 40 varves averaging 1.48 cm. The top 7 cm of the varves are weathered and iron stained.	130.7	198.9	978.7

Unit	Description (cont.)	S.T.	U.T.	C.T.
9 -	Silt layer 9 has many different types of sedimentary structures, from the bottom to top they are: continuous horizontal laminations (2.5 cm), curl flow (1 cm), continuous horizontal laminations (8.5 cm), discontinuous horizontal laminations (1 cm), type B ripple-drift cross-laminations (7.5 cm), type A ripple-drift cross-laminations (5 cm), type B dune-drift cross-laminations (60 cm), type A ripple-drift or dune-drift cross-laminations (29 cm), type B dune-drift cross-laminations (18 cm), type A dune-drift cross-laminations (19 cm), type A ripple-drift cross-laminations (9 cm), continuous horizontal laminations (6 cm). The apparent current direction for all sedimentary structures is westward. There are 34 varves averaging 2.16 cm.	160.4	241.0	779.8
8 -	The silt layer has continuous horizontal laminations overlain by 40 varves averaging 1.44 cm. The top 3.4 cm are weathered and iron stained.	19.3	77.0	538.8
7 -	Small scale wave ripples overlie the curl flow structures which in turn are overlain by continuous horizontal laminations. There are 31 varves averaging 2.43 cm. The basal varves are very thick; varve 2, 19.9 cm; varve 9, 9.5 cm; and varve 10, 12.8 cm. The top 5.1 cm are weathered and iron stained.	24.2	99.5	461.8

Unit	Description (cont.)	S.T.	U.T.	C.T.
6 -	Above the curl flow structure, small scale wave ripples are preserved, as in unit 4. The rest of the silt has continuous horizontal laminations overlain by 26 varves averaging 2.07 cm. The top of this unit also has curl flow structures.	13.7	75.8	362.3
5 -	The basal part of the silt has small wave ripple laminae, similar to those in unit 4, the rest of the silt has continuous horizontal laminations overlain by 39 varves averaging 2.49 cm. Varve 2 is 10.1 cm thick and decreases in thickness to 1.5 cm thick for varve 9. Varves 10, 11, 12 (5.1 cm, 7.5 cm, 8.0 cm) are also thick but decrease upward to an average of 1.0 cm in thickness. The top of varve unit 5 and basal silt unit 6 show curl flow structures with an apparent westward current direction.	17.5	111.2	286.5
4 -	The basal 1 cm of the silt layer has discontinuous horizontal laminations interrupted by cross-laminations with an apparent eastward current direction. Small scale wave ripples (6 mm amplitude, 3.5 cm wavelength) with straight, parallel crests overlie the discontinuous laminations. There is a transition zone between the underlying wave ripples and overlying continuous horizontal laminations. The entire varve sequence is weathered and no count was possible. The varves are overlain by a lens of channel gravels which are iron stained and slightly cemented by $CaCO_3$. The upper surface of the	38.3	50.9	175.3

Unit	Description (cont.)	S.T.	U.T.	C.T.
4 -	gravels and varves unit are slightly scoured.	38.3	50.9	175.3
3 -	The silt layer has continuous horizontal laminations overlain by 16 varves averaging 2.65 cm. Varve 8 is a thick (7.2 cm) dark layer with thin wisps of silt. The top 2.7 cm of the varve sequence has a dry, crumbly texture, which appears to be a weathered horizon. This horizon is also iron stained and slightly scoured.	7.2	51.2	124.4
2 -	The silt layer has continuous horizontal laminations overlain by 18 varves averaging 1.81 cm in thickness. The varves are overlain by iron stained, festooned cross-bedded sand and gravel lens, with apparent current direction to the west. The upper surface of the gravels and varves have been slightly scoured.	9.3	41.6	73.2
1 -	The silt layer has continuous horizontal lamination overlain by 18 varves averaging 1.14 cm in thickness. The top 6.7 cm of the varve sequence is a thick dark layer with thin wisps of silt within it. The varves are overlain by an iron stained pebble lens, with westward imbrication of the grains. The gravel lens also has festooned cross-beds and appear to be stream deposited. The upper surface of gravels and varves are slightly scoured.	5.3	31.6	31.6

Locality JV is located approximately 7 miles north of Arlee, Montana along Highway 93 on the north side of the road. Approximately 30 feet of sediment is exposed. There were 308 varves counted in the 17 stratigraphic units. Only one silt layer is described below in order to document all the sedimentary structures reported on. The silt layer overlies a 15 foot thick mud flow deposit. There is a stream channel cut into the right corner of the mud flow (see section concerning soil horizons and figs. 25 and 26).

<u>Unit</u>	<u>Description for base to top of silt layer</u>
4	Type B dune-drift (7.5 cm), continuous horizontal laminations (11 cm), sinusoidal ripple laminations (1 cm), continuous horizontal laminations (3 cm), curl flow (1.5 cm), discontinuous horizontal laminations (4 cm), type A ripple-drift (11.5 cm), curl flow (6.5 cm), type A ripple-drift (10 cm), curl flow (4 cm), continuous horizontal laminations (8 cm), curl flow (2 cm), continuous horizontal laminations (3 cm), curl flow (1.5 cm), continuous horizontal laminations (15 cm), curl flow (5 cm), type B dune-drift (10.5 cm), type A ripple-drift (10.5 cm), sinusoidal (5 cm), type B ripple-drift (7 cm), sinusoidal (3cm), type B ripple-drift (3.5 cm), type A ripple-drift (9 cm), sinusoidal (9 cm), type A ripple-drift (8 cm), type B dune-drift (14 cm), and continuous horizontal laminations (53 cm).

Locality MV is located approximately 3 miles west of the Kalispell-Glacier Park turnoff (Highway 93) on Interstate 10 on the north side of the road. There were 273 varves measured in the 10 stratigraphic units. The stratigraphic units are similar to those at locality SP and will not be described. However, wood samples for radiocarbon dates were collected from the festoon cross-bedded sand lens of unit 2.

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