

THESIS APPROVAL

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## ABSTRACT

An abstract of the thesis of David H. James for the Master of Science in Geology presented June 14, 2002.

Title: Stratigraphy, Sedimentology, and Geochemistry of Missoula Flood Rhythmites in the Northern Willamette Valley, Oregon.

A detailed stratigraphic, sedimentologic, and geochemical study was performed on Missoula Flood deposits at two sites in the northern Willamette Valley, Oregon: along Greeley Avenue in north Portland and near the town of Dayton, Yamhill County.

The Missoula Floods were a series of late Pleistocene (15,300-12,700 years b.p.) glacial outburst floods that left significant slackwater deposits in the Willamette Valley of Oregon.

The 21.9 m stratigraphic exposure at Greeley Avenue contains at least 25 rhythmite couplets (graded flood beds) ranging from 0.07 m to 4.13 m thick (average =  $0.91 \text{ m} \pm 0.94 \text{ m}$ ). Particle size varies from silt to gravelly sand with boulders up to 45 cm in diameter, indicative of a variable and high-energy depositional environment.

The 14.6 m stratigraphic exposure near Dayton, Oregon contains least 30 rhythmite couplets ranging from 0.28 m to 0.97 m thick. Average thickness of the upper 13 beds is  $0.34 \text{ m} \pm 0.06 \text{ m}$ , and average thickness of the lower 17 beds is  $0.60 \text{ m} \pm 0.15 \text{ m}$ . Particle size for rhythmite bed bottom sections range in graphic mean from  $6.90 \phi$  ( $0.0086 \text{ mm}$ )  $\pm 1.77 \phi$  to  $4.63 \phi$  ( $0.041 \text{ mm}$ )  $\pm 1.07 \phi$ ; Inclusive Graphic Standard Deviation ranges from  $\pm 0.93 \phi$  (moderately sorted) to  $\pm 2.23 \phi$  (very poorly sorted). Rhythmite bed top sections range in graphic mean from  $6.00 \phi$  ( $0.0156 \text{ mm}$ )  $\pm 2.01 \phi$  to  $6.87 \phi$  ( $0.0088 \text{ mm}$ )  $\pm 1.70 \phi$ ; Inclusive Graphic Standard Deviation ranges from  $\pm 1.66 \phi$  (poorly sorted) to  $\pm 2.01 \phi$  (very poorly sorted).

Instrumental Neutron Activation Analysis (INAA) results at Dayton show increases in iron ( $3.49 \% \pm 0.04 \%$  to  $5.61 \% \pm 0.05 \%$  by weight), and scandium ( $13.90 \text{ ppm} \pm 0.05 \text{ ppm}$  to  $19.25 \text{ ppm} \pm 0.09 \text{ ppm}$ ) with a corresponding decrease of chromium ( $71.99 \text{ ppm} \pm 1.78 \text{ ppm}$  to  $43.72 \text{ ppm} \pm 1.46 \text{ ppm}$ ) through time.

The chemical transition may represent the stripping of glaciogenic loess of the Palouse Silt Formation and establishment of well-defined Columbia River Basalt Group (CRBG) bedrock flood pathways in the source areas of eastern Washington.

STRATIGRAPHY, SEDIMENTOLOGY, AND GEOCHEMISTRY OF MISSOULA  
FLOOD RHYTHMITES IN THE NORTHERN WILLAMETTE VALLEY, OREGON

By

DAVID H. JAMES

A thesis submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE  
in  
GEOLOGY

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## **Dedication**

This opus is dedicated to my mother Grace, my father Max, my precious, lovely, beautiful, and talented wife Mary Ann, my patron professors (you know who you are), the Powers that instill me with a love and conversation with the landscape, and all those who believed in me and never lost faith.

## Acknowledgments

I would like to thank the following for their gracious help and support:

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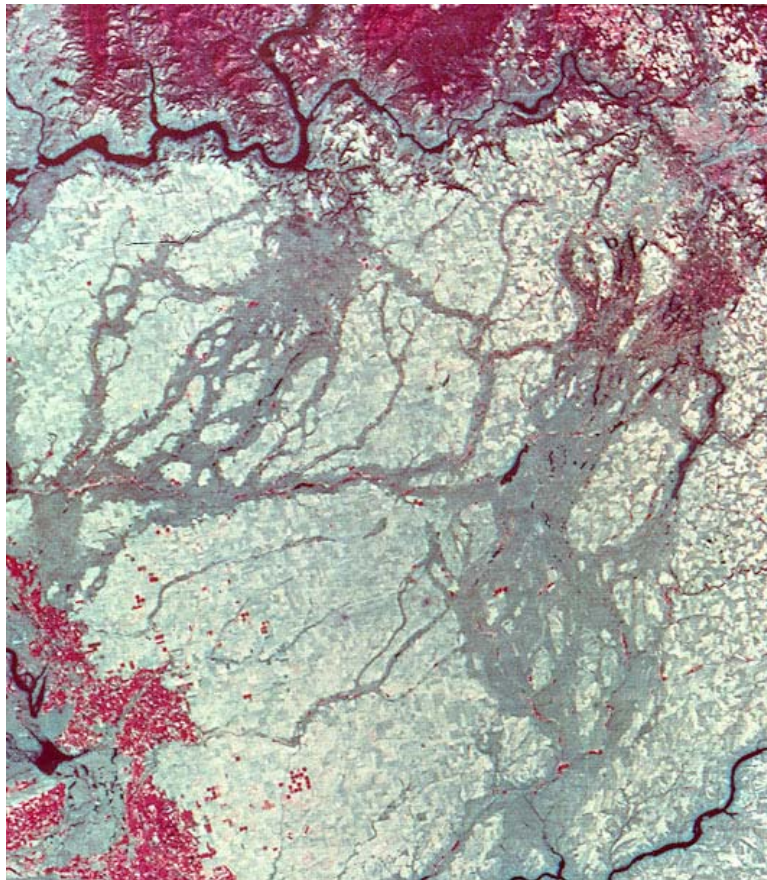
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## Chapter 1 - Introduction

The Missoula Floods were a series of jokulhlaup floods emanating out of northwestern Montana between approximately 15,300 and 12,700 years ago (Baker, 1973; Waitt, 1984; Waitt, 1985). It has been estimated that there may have been up to 90 cataclysmic flood events in succession (Atwater, 1984) resulting from the breaching of glacial dams across the Clark Fork River near Lake Pend Oreille, Idaho. The breaching of the glacial dams allowed the sudden, catastrophic release of the impounded water of Pleistocene Lake Missoula (Pardee, 1942; Baker, 1973; Waitt, 1985; Atwater, 1984). Up to 2000 km<sup>3</sup> of water was released in each successive flood event (Pardee, 1942; Baker, 1973; Waitt, 1985; Atwater, 1984; Alt, 2001). These cataclysmic floods flowed across northern Idaho and eastern Washington entraining sediment and carving the Channeled Scablands of the high desert, leaving a scar in the landscape visible from space (Fig. 1). Peak flows through the Wallula Gap in southern Washington to the Columbia River Gorge have been estimated at over 17 million m<sup>3</sup>/s (Baker, 1973; Baker and Komar, 1987). While confined within the Columbia River Gorge, flow heights up to the 330 m (1100 ft.) elevation mark have been estimated for some of the larger events (Baker, 1973; Baker and Komar, 1987).

The Willamette Valley in northwestern Oregon backfilled during some of these flood events as far upstream as Eugene, Oregon, forming Pleistocene Lake Allison as the turbid floodwaters became hydraulically dammed behind the bend in the Columbia River at the Tualatin Mountains known as Kalama Gap (Allison, 1935; Allen et al.,

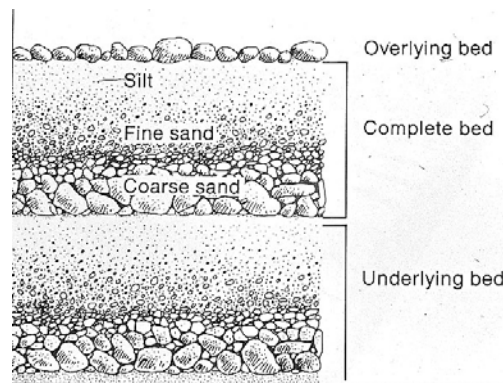
1986). Estimates based on the location and position of ice-rafted glacial erratics have indicated depths of this inundation in the Willamette Valley to have reached an elevation of approximately 120 m (400 ft.) in the Portland, Oregon, area (Allison, 1935; Allen et al., 1986). After each flood event, this ephemeral lake would then drain back out the mouth of the Willamette River and down the Columbia River to the Pacific Ocean.



**Figure 1. Landsat image of the Channeled Scabland, NE Washington.**

Rhythmite deposits (rhythmically graded sequences of sediment beds) attributed to these prehistoric deluges have been found at several localities in northwestern Oregon and eastern and southeastern Washington, usually consisting of rhythmite couplet sequences of silty sands overlain by silts and clays (Bjornstadt, 1980; Waitt, 1985; Glenn, 1965). Each rhythmite couplet (relatively coarse-grained lower section and relatively finer-grained upper section) has been inferred to represent a distinct and separate flood event (Waitt, 1985). Each rhythmite couplet is formed as the coarse material is deposited during the initial influx of an individual flood event, and the fines drop out of suspension during the time of maximum ephemeral lake levels and drainage.

Rhythmites were first described as a type of sedimentary bed in the analysis of turbidity current deposits in fans on the sea floor (Bouma, 1962). The beds found as a result of successive flood deposition differ in genetic origin from those described by Bouma but generally follow the same graded bed form in cross section (Fig. 2).



**Figure 2. Idealized rhythmite bed cross section.**

Up to 90 successive and stratigraphically continuous rhythmite beds have been found at several widely spaced localities in eastern Washington (Atwater, 1984; Waitt, 1985) (Fig. 3) and in northwestern Oregon (Glenn, 1965; James, 1997; James et al., 1998). In Oregon, deposits attributed to these floods have been given the formation name Willamette Silt (Glenn, 1965). Recently, the name Hanford Formation has been suggested as a formal name for all cataclysmic flood deposits in northern Idaho, eastern Washington, and northwestern Oregon attributable to the Missoula Floods (Bjornstad et al., 2002). Rhythmite beds form the uppermost stratigraphic unit of the valley floors (except in scour areas) in the entire Portland Basin, and also in the Tualatin, Yamhill, and Willamette Valleys of northwestern Oregon.



**Figure 3. The Touchet Beds - rhythmite beds near Walla Walla, Washington.**

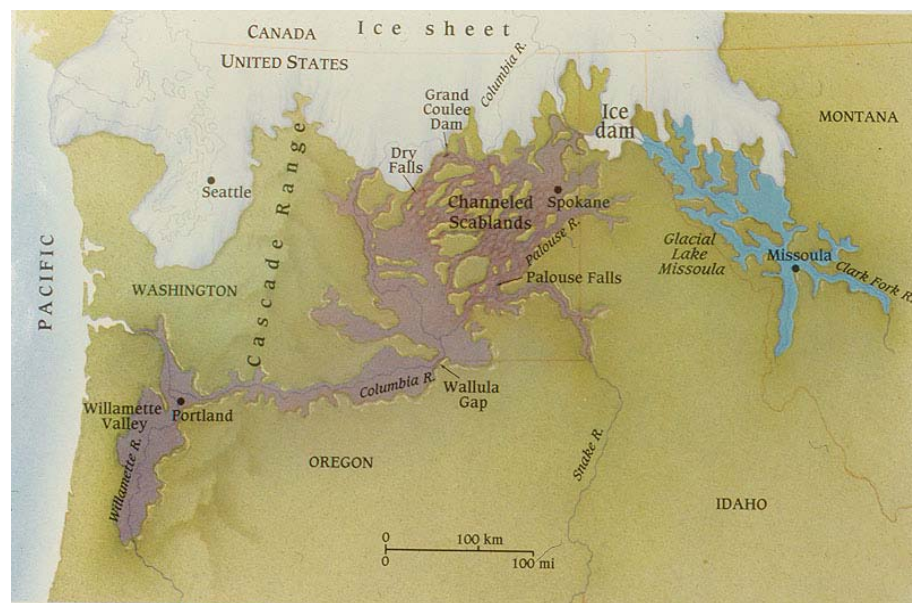
## *Background*

The first recognition that a gigantic flood event had impacted the Pacific Northwest region was by J Harlan Bretz in the 1920's (Bretz, 1923; 1925; 1929). J Harlan Bretz performed extensive fieldwork in the Channeled Scabland in eastern Washington, mapping and cataloging the many geomorphic features there. He postulated that the enormous dry cataraacts and coulees could only have formed as the result of flood erosion on a gigantic scale. His evidence included giant ripple bars composed of boulders with wavelengths of hundreds of feet, large eroded bedrock coulees with undersized streams or no streams present at all, and the presence of huge plucked boulders strewn across the landscape, out of stratigraphic position. He believed that a single tremendous flood, which he named the Spokane Flood, had emanated from east of the Spokane, Washington region and had carved the landscape in its passing.

Bretz presented his evidence to a forum of leading geologists of the day and was largely scoffed at for appealing to catastrophism to explain the geomorphic features. In fact, he was using the finest tradition of modern uniformitarianism in that he presented the most logical, physically feasible process that could produce the geomorphic effects that he documented in the field. His one self-admitted drawback was that he could find no source of water to fuel the inferred flood.

Bretz was redeemed with the publication, in 1942, of a paper by John Pardee (1942), which outlined the existence of Glacial Lake Missoula in the intermontane valleys of the northern Rocky Mountains. Pardee presented evidence that a large lake

(up to 2500 cubic kilometers) had formed in the network of valleys of the Rocky Mountains. Pardee named this lake Glacial Lake Missoula due to the presence of clearly defined wave-cut terraces in the hills above Missoula, Montana. Pardee believed that the lake formed due to the damming of the Clark Fork River in northern Idaho by a glacial lobe surging down the Purcell Trench in British Columbia and northern Idaho (Fig. 4). Pardee further presented evidence that this lake had catastrophically drained, possibly several times. Pardee never explicitly linked the drainage of Glacial Lake Missoula to the floods hypothesized by Bretz, but the implication was clear. Bretz had his source of water.



**Figure 4. Idealized Map of the Pacific Northwest at the time of the Missoula Floods.**

Later studies put the number of times that Glacial Lake Missoula may have drained during the most recent Ice Ages at between approximately 90, in the Sanpoil Arm of Glacial Lake Columbia near the source (Atwater, 1984), to about 40 farther downstream in the Touchet Beds of southeastern Washington (Waitt, 1985) and in northwestern Oregon (Glenn, 1965). The cataclysmic floods resulting from the drainage of Glacial Lake Missoula have been alternatively called the Spokane Flood(s), the Missoula Floods or the Bretz Floods, in honor of J Harlan Bretz (Allen et al., 1986; Alt, 2001).

### *Aims and Objectives*

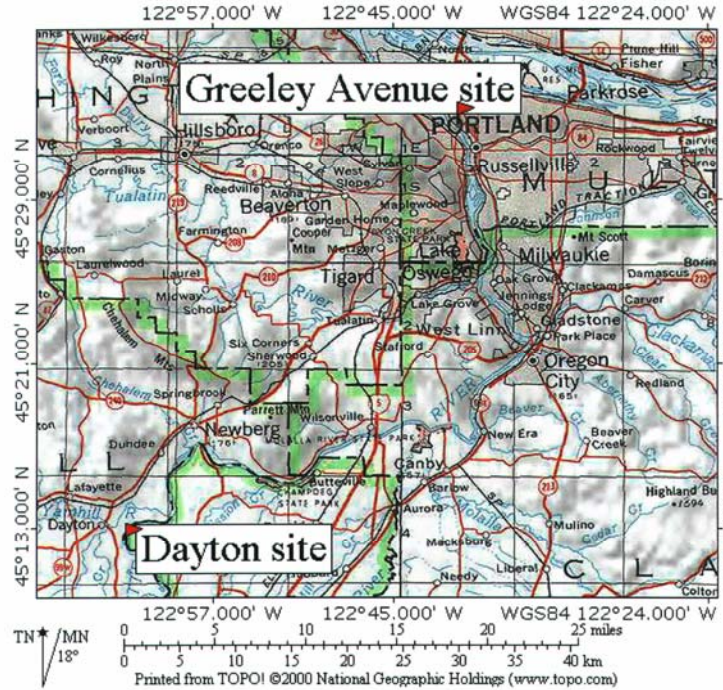
This study presents stratigraphic, sedimentological, and geochemical information gathered from deposits left by the Missoula Floods in the northern Willamette Valley of Oregon. Detailed stratigraphic measurements were taken of the overall flood sequence and individual constituent rhythmite beds at two localities. In addition, a detailed sedimentological and geochemical study was performed on one of the localities.

This study seeks to characterize the deposits attributed to the Missoula Floods in the northern Willamette Valley, Oregon. Similarities and differences between the two exposures will be discussed. The implications of the physical nature of the deposits at the two sites will be discussed as to how they relate to the sequence of Missoula Flood events in the Willamette Valley and also to the source area of these cataclysmic flood events. Furthermore, this study seeks to describe and define stratigraphic, sedimentary,

and geochemical trends that can be applied as predictors for stratigraphic position in other exposures of Missoula Flood deposits in the Willamette Valley and elsewhere.

It is hoped that this study will shed light on the sequence of events in this phenomenal series of floods. It is also hoped that this study will provide a backdrop for study of additional exposures of Missoula Flood sediments in the Willamette Valley and elsewhere in the Pacific Northwest.

## Chapter 2 - Study Sites



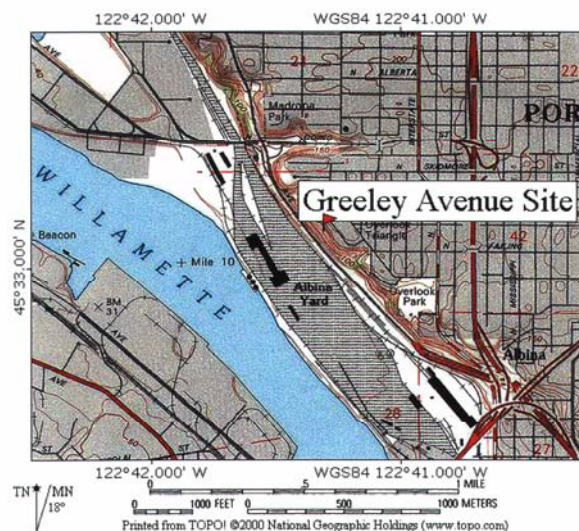
**Figure 5. Location of study sites in NW Oregon.**

Two sites in the northern Willamette Valley were chosen for this study (Fig. 5). Both exposures of Missoula Flood derived sediments were revealed as the result of landslide activity during the extreme winter storm events of February 1996. Missoula Flood deposits make up the uppermost stratigraphic unit at both study sites.

### *Greeley Avenue Site*

The first site is located along North Greeley Avenue in Portland, Oregon (Fig. 6). The site is located at latitude 45° 33.087' N and longitude 122° 41.294' W. The

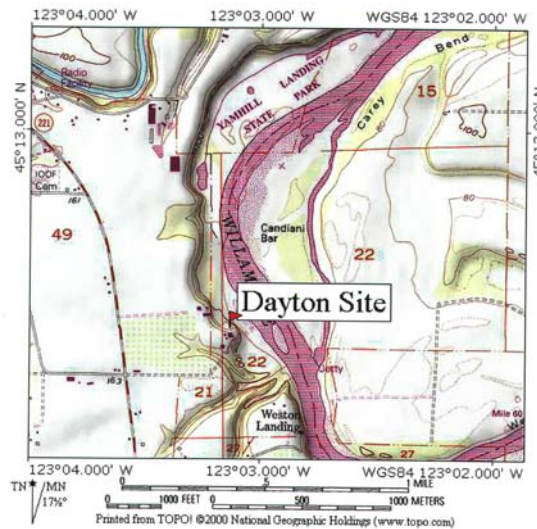
exposure at Greeley Avenue is on a south facing bluff overlooking the Willamette River. This bluff is on the southwestern edge of Alameda Ridge, an approximately 20 km long pendant bar formed behind Rocky Butte during the floods. The exposure ranges from approximately 30 to 50 meters elevation relative to mean sea level (m.s.l.). Slope angle ranges from 35 to 40 degrees, increasing toward the top of the exposure. The increase in slope angle corresponds to a qualitatively observed trend of fining of the particle sizes toward the top of the overall exposure. Deposits at the Greeley Avenue site consist of light tan to dark gray coarse sands and gravel to sandy silt. Particle sizes in the coarse fraction at this exposure range up to gravels, cobbles, and boulders. Twenty-five successive rhythmite couplet beds are exposed at the Greeley Avenue site.



**Figure 6. Greeley Avenue site location in Portland, Oregon.**

## Dayton Site

The second site is located farther south along the Willamette River on the Ray Geller Farmstead outside of the town of Dayton, Oregon (Fig. 7). It is located at latitude  $45^{\circ} 12.460' N$  and longitude  $123^{\circ} 3.207' W$ . along a northeast facing bluff overlooking the Willamette River at Carey Bend. The exposure at Dayton ranges in elevation from approximately 35 to 50 meters m.s.l. Slope angle at the site ranges from approximately 30 to 40 degrees, increasing toward the top of the exposure. Rhythmite beds at this site are typical of those found in the Willamette and Yamhill Valleys, consisting primarily of light tan to light gray, coarse to fine silt with trace fine sand. The exposure here is located near those studied by Glenn (1965) and is similar in character. Thirty successive rhythmite couplet beds are exposed at the Dayton site.



**Figure 7. Dayton site location**

### *Other Sites*

A third site, located in southeast Portland on the east side of the Willamette River above Ross Island at latitude 45° 29.459' N and longitude 122° 39.384' W, was looked at for this study but rejected due to the limited stratigraphic exposure. The Ross Island site was also revealed as a result of landsliding during the February 1996 storms, but only the upper rhythmites were exposed. Samples were taken from the upper five rhythmite beds, and these were used in part of the geochemical analysis.

Other sites were also used as part of the geochemical analysis, but I did not visit these during the course of this study. Samples for INAA analysis were obtained and provided by Terry Tolan from upper section rhythmites exposed in a road cut near Walla Walla, Washington. Also, samples from the Palouse Silt Formation in eastern Washington (Lawes, 1997) and the U.S.G.S. geochemical standard sample for the Columbia River Basalt Group were considered and included in the geochemical study as reference samples.

## Chapter 3 - Methods

### *Stratigraphic Measurement*

All field measurements of stratigraphic thickness were taken using a tape measure and clinometer during a traverse of the face of each exposure. Trigonometric functions were then used to derive true vertical thickness from the measured slope thickness and the slope angle as measured from the horizontal.

Determination of the stratigraphic contact of each specific rhythmite unit was based on field observation. Determination of the upper vertical boundary of each rhythmite was based on an observable, non-gradational change in particle size, color, and character of the constituent sediments (Fig. 8). The lower section of the rhythmite couplets, at both sites, tended to be darker and grayer in color with a more sandy texture, whereas the upper sections tended to be lighter in color with more of a silt loam texture.

Measurements taken and tabulated include overall thickness of the exposure, individual rhythmite couplet bed thickness, and thickness measurements of the top (relatively fine-grained) and bottom (relatively coarse-grained) sections of each rhythmite.



**Figure 8. Stratigraphic boundary between rhythmities at Greeley Avenue.**

### *Sample Collection*

Samples were collected in the field from each measured rhythmite at the time of survey. After stratigraphic measurement, one to two kilogram samples of representative sediment were carefully collected from the approximate centers of both the fine (top) and coarse (bottom) sections of each individual rhythmite bed. The samples were then

sealed in plastic bags and labeled. Each sample was given a prefix designating sample locality (D = Geller Farm, Dayton, Oregon; G = Greeley Avenue, Portland, Oregon) along with a number designating the rhythmite bed's relative stratigraphic position down from the top identified rhythmite of the exposure (bed numbering for the Greeley Avenue site was adjusted during analysis to reflect an apparent field correlation between maximum thickness beds at the two sites). A suffix of T (top) or B (bottom) was then assigned to each sample based on the sample location within the individual rhythmite couplet. For example, the sample labeled D-30T would designate the fine (upper) section of the thirtieth rhythmite down from the top at the Dayton, Oregon locality. Other sample localities, used chiefly in the geochemical analysis, use the sample prefixes WW = Walla Walla (the road cut rhythmite exposure), RI = Ross Island exposure, BR = Portland Hills Silt (Lawes, 1997), BR-CR = Palouse Silt Formation (Lawes, 1997), and CRB ST1 = a Columbia River Basalt Group U.S.G.S. geochemical standard. All reported results use this sample nomenclature.

### *Particle Size Analysis*

Quantitative particle size analysis was completed on the lower (relatively coarse-grained) section of each rhythmite bed at the Dayton locality. This locality was chosen because of the more uniform characteristics of the sedimentary beds there. It was felt that the Greeley Avenue site was too highly variable and chaotic due to its location in a high-energy constriction and confluence of flood flows. Sampling for particle size analysis at the Greeley Avenue site is also problematic in the larger flood event beds. Sample amounts needed to obtain a representative and statistically valid particle size

distribution in beds containing boulders up to 45 cm in diameter were simply too large for the scope of this project and the equipment available. The Dayton site offered sediments deposited in a more slackwater environment where subtle variance in particle size distribution could be observed. This is in concert with studies performed on Missoula Flood deposits elsewhere (Bjornstadt, 1980; Atwater, 1984; Waitt, 1984 and 1985). Particle size distribution of rhythmites at the Greeley Avenue exposure will be described qualitatively in the results section.

In addition, particle size analysis was performed on the upper (relatively fine-grained) section of five randomly selected rhythmite couplet beds from the Dayton locality. This was done to test the hypothesis that there would be little to no variation in the upper sections of the rhythmites. The upper section of each rhythmite bed is thought to represent deposition of fine sediment out of suspension under static flow conditions. This would occur during maximum lake levels and drainage of ephemeral Pleistocene Lake Allison during each flood event. As such, the upper section of each rhythmite should be similar in particle size distribution. This is in contrast to the lower section of each rhythmite, which would be subject to variation due to variable flow conditions during sediment influx related to the magnitude of the individual flood event.

Particle size analysis was performed using standard sieve and pipette methods according to P.R. Day (1965). After separating the coarse fraction ( $>0.063$  mm) from the fine fraction ( $<0.063$  mm) by washing each sample through a #230 mesh sieve (opening size 0.063 mm), the coarse fraction was dried and separated into constituent

particle size classes using mechanical separation through graduated sieves. Each coarse size class was weighed and the results tabulated. The fine fraction was separated into its constituent  $\phi$  size classes using the pipette method, based on Stoke's Law of particle settling velocity in a fluid. Weight and weight percent results of the pipette analysis were tabulated and integrated with the sieve analysis results to obtain a total particle size distribution for each sample. Initial sample weight and recovered sample weight was recorded for each sample. If procedural error resulted in a discrepancy of more than 10% between the initial and recovered weights, the sample was run again.

For the purpose of analysis, this study defines the major particle size classes (sand, silt, clay) in accordance with the accepted geologic ranges as follows: sand = 2 mm - 0.063 mm, silt = 0.063 mm - 0.002 mm, and clay = <0.002 mm. No particles greater than 2 mm in diameter were encountered in the quantitative particle size analysis.

Results were graphed as both a weight percent per particle size fraction distribution curve and as a cumulative weight percent curve. From this information the Median, Graphic Mean, Inclusive Graphic Standard Deviation, and Skewness were calculated according to the equations presented in Folk (1974). Results are presented in Appendix A.

### *Instrumental Neutron Activation Analysis*

Instrumental Neutron Activation Analysis (INAA) is the process of irradiating samples by neutron bombardment and then recording radioactive decay events, as represented by gamma rays re-emitted at wavelengths characteristic to various elements (Muecke, 1980). The number and spectral position of such gamma rays of characteristic wavelength can be used to determine the elemental composition of a sample to parts per million (ppm) level of resolution.

From the set of samples collected from each rhythmite it was determined that only the fine (upper) portion of each rhythmite would be used for geochemical assay. This was done to take advantage of the higher degree of homogeneity in the mostly silt- and clay-sized sediments present in the upper portion of each rhythmite bed. Also, the upper portions of each rhythmite had lower concentrations of mostly non-reactive quartz and feldspar than the lower, more sand-rich, portions. Finally, it was felt that using sediment from the more homogeneous and fine-grained upper would aid in avoiding the “nugget” effect in the geochemical analysis. The “nugget” effect means the potential for a non-representative, larger-sized grain to dominate the chemical signature and throw off the general chemical assay of the sample as a whole (Dr. Marvin Beeson, personal communication, 1997).

From initial split sample amounts varying from 30 to 50 grams, each sample was ground and homogenized using a mortar and pestle. The homogenized sample was then split further down to a final sample amount of approximately 1 gram (or, more

appropriately, approximately 1 cm<sup>3</sup> since the geometry of the sample was more important than exact weight continuity). The weight of each final split section was measured to a tolerance of .001 of a gram. The weighed samples were placed into 1-dram polystyrene vials, sealed, and then double-sealed into a labeled 10-dram polystyrene vial for irradiation.

The samples were taken to the Research Nuclear Reactor facility at Reed College, Portland, Oregon. There they were irradiated for one hour at 250 kilowatts of power using a neutron radiation source. After a prescribed holding time (approximately 36 hours) to avoid harmful radiation effects of certain elements that have dangerously high levels of re-emitted radioactivity due to short half-lives, the samples were removed from the reactor. The samples were then immediately placed in shielded containers and transported back to Portland State University. The irradiated samples were analyzed on a germanium crystal-based, multi-band spectrum detector/analyzer. Data acquisition was performed using MAESTRO, a PC software designed for INAA data collection and analysis. Data manipulation was performed through use of Microsoft Excel™ spreadsheet software.

## Chapter 4 - Results

### *Stratigraphy*

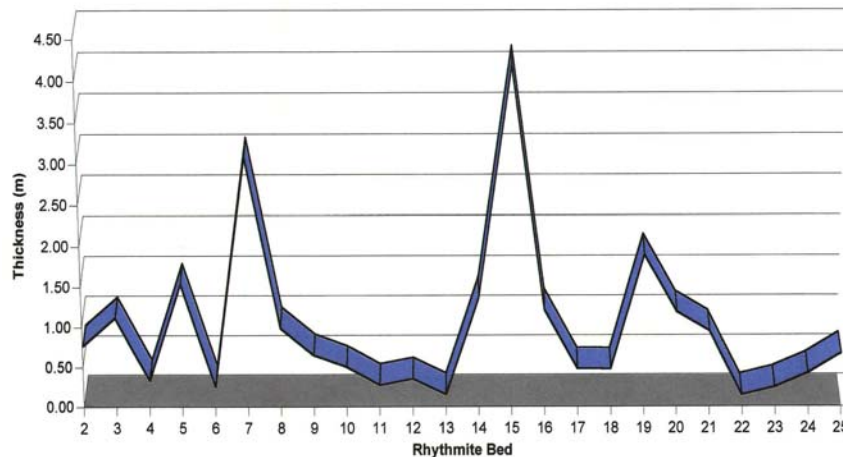
Measurements taken at the two study sites include overall stratigraphic thickness of each exposure, thickness of individual rhythmite beds, and thickness of the upper (relatively fine-grained) and lower (relatively coarse-grained) sections of each rhythmite, where possible. More rhythmites than those measured are believed to exist both above and below the exposures at both sites. One to two rhythmite beds may be present above each measured exposure, hidden beneath heavy vegetation. A larger and unknown number of rhythmite beds may be present below each exposure, obscured by colluvium in the form of landslide debris. Results of stratigraphic measurement are presented in Table 1.

**Table 1. Summary of stratigraphic measurements.**

Greeley site			Dayton site		
Bed	Thickness (m)		Bed	Thickness (m)	Per Bed (m)
			D-1T	0.15	
			D-1B	0.25	0.40
		Per Bed (m)	D-2T	0.10	
			D-2B	0.31	0.41
			D-3T	0.08	
G-2B	0.70	0.70	D-3B	0.31	0.38
G-3T	0.20		D-4T	0.05	
G-3B	0.85	1.05	D-4B	0.23	0.28
G-4T	0.08		D-5T	0.08	
G-4B	0.18	0.26	D-5B	0.18	0.25
G-5T	0.18		D-6T	0.08	
G-5B	1.29	1.47	D-6B	0.20	0.28
G-6T	0.09		D-7T	0.08	
G-6B	0.09	0.18	D-7B	0.25	0.33
G-7T	0.05		D-8T	0.08	
G-7B	2.97	3.02	D-8B	0.30	0.38
G-8T	0.03		D-9T	0.08	
G-8B	0.89	0.92	D-9B	0.23	0.31
G-9B	0.58	0.58	D-10T	0.05	
G-10T	0.02		D-10B	0.25	0.31
G-10B	0.41	0.43	D-11T	0.08	
G-11T	0.09		D-11B	0.20	0.28
G-11B	0.11	0.20	D-12T	0.08	
G-12B	0.28	0.28	D-12B	0.31	0.38
G-13T	0.03		D-13T	0.08	
G-13B	0.05	0.08	D-13B	0.33	0.41
G-14T	0.39		D-14T	0.10	
G-14B	0.91	1.30	D-14B	0.53	0.64
G-15T	0.03		D-15T	0.08	
G-15B	4.10	4.13	D-15B	0.89	0.97
G-16T	0.63		D-16T	0.10	
G-16B	0.52	1.15	D-16B	0.46	0.56
G-17T	0.07		D-17T	0.08	
G-17B	0.34	0.41	D-17B	0.48	0.56
G-18T	0.04		D-18T	0.10	
G-18B	0.36	0.40	D-18B	0.41	0.51
G-19T	0.77		D-19T	0.18	
G-19B	1.06	1.83	D-19B	0.36	0.53
G-20T	0.06		D-20T	0.18	
G-20B	1.06	1.12	D-20B	0.23	0.41
G-21T	0.04		D-21T	0.13	
G-21B	0.84	0.88	D-21B	0.36	0.48
G-22T	0.06		D-22T	0.15	
G-22B	0.01	0.07	D-22B	0.51	0.66
G-23T	0.04		D-23T	0.13	
G-23B	0.13	0.17	D-23B	0.31	0.43
G-24T	0.06		D-24T	0.13	
G-24B	0.29	0.35	D-24B	0.33	0.46
G-25T	0.03		D-25T	0.13	
G-25B	0.57	0.60	D-25B	0.48	0.61
G-26T	0.35	0.35	D-26T	0.10	
Total:	21.93		D-26B	0.36	0.46
			D-27T	0.15	
			D-27B	0.61	0.76
			D-28T	0.13	
			D-28B	0.46	0.58
			D-29T	0.20	
			D-29B	0.61	0.81
			D-30T	0.00	
			D-30B	0.81	0.81
			Total:	14.63	

## Greeley Avenue Site

Twenty-five distinct rhythmite couplet beds are present at the Greeley Avenue exposure (Figs. 9 and 10). The total stratigraphic thickness of exposed Missoula Flood sediments at Greeley Avenue is approximately 22 m. Individual rhythmite couplet bed thickness ranges from a minimum 0.07 m to a maximum of 4.13 m. Stratigraphic thickness of individual rhythmite couplets is highly variable at the Greeley exposure, but generally ranges from approximately 0.5 m to just over 1 m in thickness, with distinct (anomalously thick) exceptions (beds G-5, G-7, G-15, and G-19). Average thickness of the whole rhythmite beds is  $0.91 \text{ m} \pm 0.94 \text{ m}$ . The wide standard deviation shows the high degree of variability.



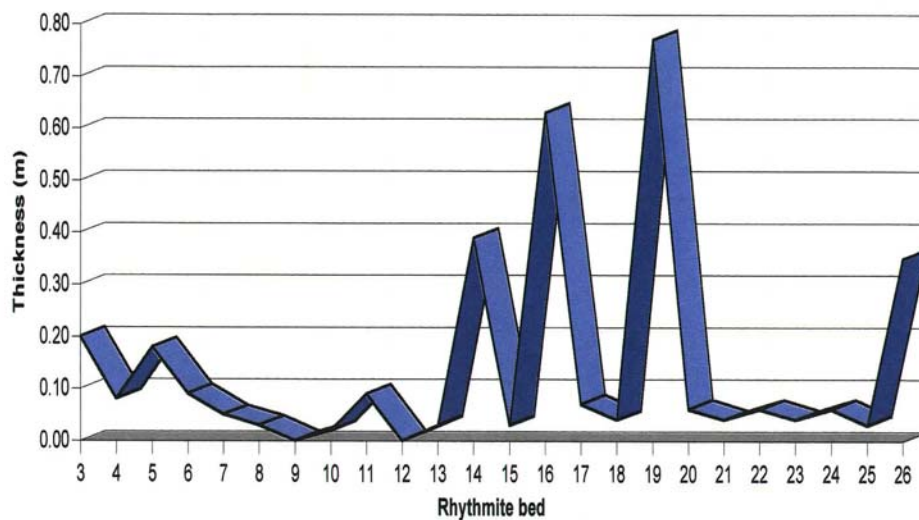
**Figure 9. Rhythmite couplet bed thickness at Greeley Avenue.**



**Figure 10. Greeley Avenue site, north Portland (note geologist in center for scale).**

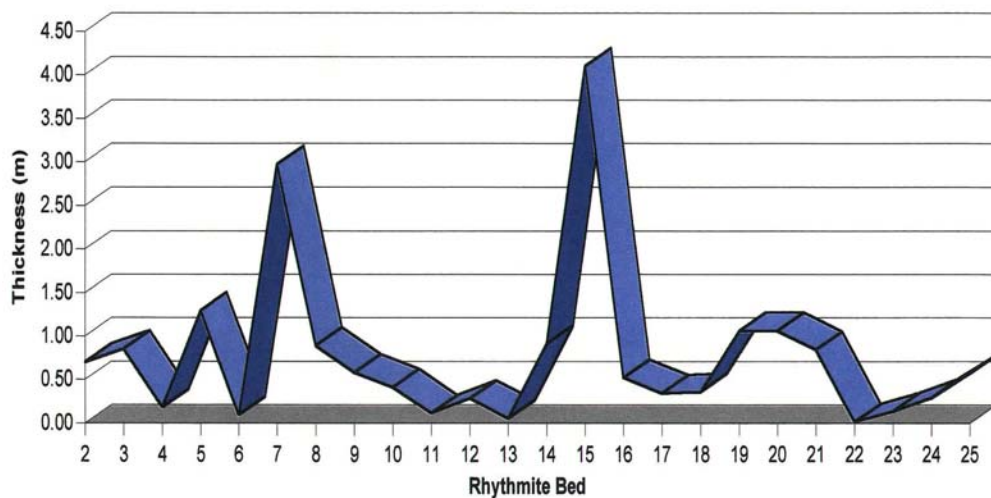
Average thickness of all of the rhythmite top sections at Greeley Avenue is  $0.14 \text{ m} \pm 0.20 \text{ m}$ , once again showing a high degree of variability. Bed G-19T is the thickest top section at  $0.77 \text{ m}$ , and bed G-10T is the smallest measurable rhythmite top at  $0.02 \text{ m}$  (beds G-9T and G-12T were not identifiable in the field and were assigned a thickness

value of 0.00 m for statistical calculation) (Fig. 11). Six rhythmite bed top sections have stratigraphic thickness more than double all others (beds G-3T, G-5T, G-14T, G-16T, G-19T, and G-26T). All other rhythmite top sections measure below 0.10 m in thickness.



**Figure 11. Rhythmite bed top section thickness at Greeley Avenue.**

Average thickness of the bottom sections of the rhythmite couplets at Greeley Avenue is  $0.77 \text{ m} \pm 0.92 \text{ m}$ . The thickest bottom section is bed G-15B at 4.10 m and the thinnest bed is G-22B at 0.01 m. Five bottom section beds are thicker than 1 m (beds G-5B, G-7B, G-15B, G-19B, and G-20B), and all others are less than 1 m in thickness (Fig. 12). Extremes in bottom section thickness do not match extremes in top section thickness.



**Figure 12. Rhythmite bed bottom section thickness at Greeley Avenue.**

The largest individual rhythmite couplet at the Greeley Avenue exposure is located in the middle of the exposure (bed G-15) and measures 4.13 m thick (nearly 7 m along slope). It is composed of very poorly sorted coarse gravels, pebbles, cobbles, and small boulders with very little interstitial fine-grained (silt and clay) material (Fig. 13). Only the upper 0.03 m of the total thickness of bed G-15 consists of fine sand and silt (G-15T). Bed G-15 lies in similar stratigraphic position (approximately in the vertical center of the exposure) within the total deposits as the thickest rhythmite couplet bed found to the south at the Dayton locality (bed D-15).



**Figure 13. Rhythmite bed G-15 at Greeley Avenue.**

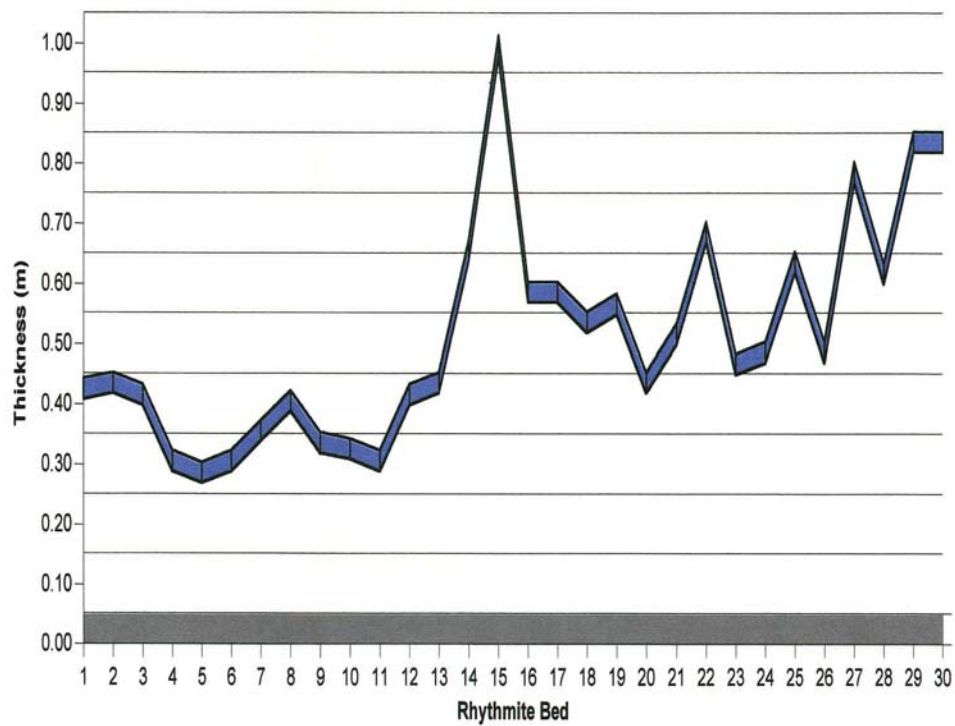
## Dayton Site



**Figure 14. Dayton site, Yamhill County (note flagging showing rhythmite bed boundaries).**

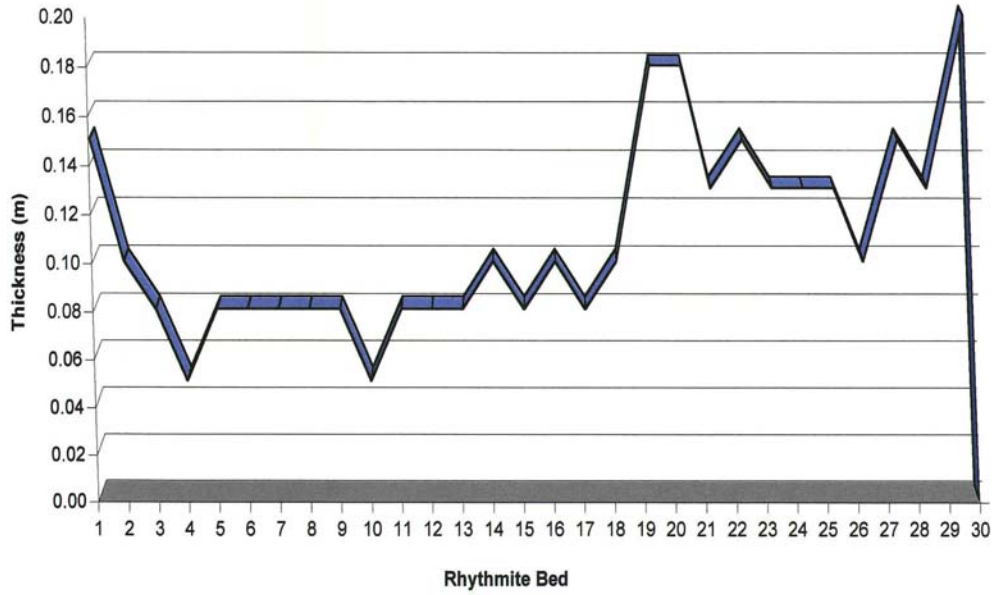
Thirty distinct rhythmite couplet beds are present at the Dayton exposure (Fig. 14). The total stratigraphic thickness of exposed Missoula Flood sediments at the Dayton site is approximately 15 m. Bed thickness at Dayton is less variable than at the

Greeley Avenue site. Thickness ranges from a minimum of 0.28 m in beds D-4 and D-6 to a maximum of 0.97 m in bed D-15 (Fig. 15). Bed thickness at Dayton generally increases from the bottom of the exposure to the middle, and generally decreases from the middle of the exposure toward the top. Anomalously thick beds are present at beds D-14, D-15, D-22, D-25, D-27, D-29, and D-30.



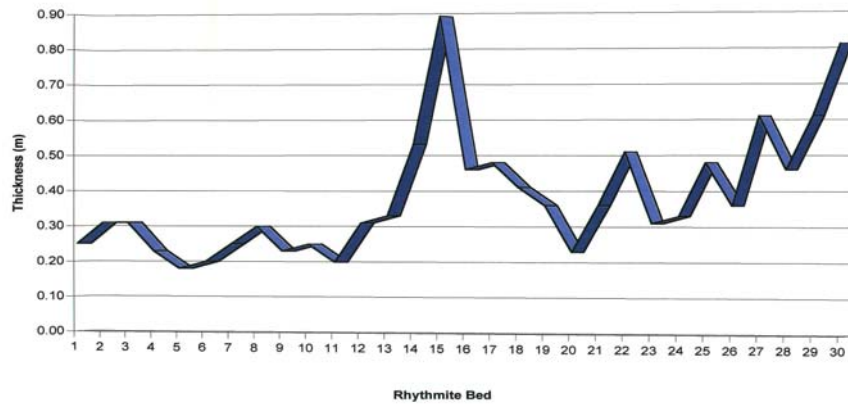
**Figure 15. Rhythmite couplet bed thickness at Dayton.**

Average thickness of the rhythmite bed top sections at Dayton is  $0.10 \text{ m} \pm 0.04 \text{ m}$  (Fig. 16).



**Figure 16. Rhythmite bed top section thickness at Dayton.**

Average thickness of the rhythmite bed bottom sections is  $0.39 \text{ m} \pm 0.17 \text{ m}$  (Fig. 17).



**Figure 17. Rhythmite bed bottom section thickness at Dayton.**

Average thickness of whole rhythmite couplet beds at Dayton is  $0.49 \text{ m} \pm 0.18 \text{ m}$ .

Perhaps a more meaningful grouping for the rhythmite beds at Dayton is if the upper beds (D-1 through D-13) and lower beds (D-14 through D-30) are separated into two groups. The upper beds (D-1 through D-13) show a rhythmite top section average thickness of  $0.08 \text{ m} \pm 0.01 \text{ m}$ , a rhythmite bottom section average thickness of  $0.26 \text{ m} \pm 0.05 \text{ m}$ , and a whole rhythmite couplet thickness average of  $0.34 \text{ m} \pm 0.06 \text{ m}$ . The lower rhythmite beds (D-14 through D-30) show a rhythmite top section average thickness of  $0.12 \text{ m} \pm 0.05 \text{ m}$ , a bottom section average thickness of  $0.48 \text{ m} \pm 0.17 \text{ m}$ , and a whole rhythmite couplet thickness average of  $0.60 \text{ m} \pm 0.15 \text{ m}$ . Looking at bed thickness this way it can be seen that the lower beds at Dayton are roughly twice as thick, overall, as the upper beds.

Both the Dayton and Greeley Avenue exposures exhibit maximum bed thickness in beds located around the middle of the exposures, and the maximum bed thickness at both exposures is located in similar stratigraphic position within the overall exposure (beds G-15 and D-15).

### *Particle Size Analysis*

#### Dayton Site

Particle size distribution trends observed on the lower (relatively coarse) section of the rhythmite couplet beds found at the Dayton site exhibit characteristics that closely compliment the results of the stratigraphic analysis. Key particle size results are

tabulated in Table 2. Inclusive Graphic Mean results range from a minimum particle size of 6.90  $\phi$  (0.0086 mm) in beds D-3B and D-4B to a maximum of 4.63  $\phi$  (0.041 mm) in bed D-17B. The results show that the chief particle size deposited during the first two floods falls into the 6  $\phi$  (0.016 mm), or medium silt, size range. The mean particle size then increases to approximately 5  $\phi$  (0.031 mm), or coarse silt, by the third flood event. The mean particle size remains near the 5  $\phi$  (0.031 mm) size class until the last six flood events (D-6B through D-1B) except in beds D-24B, D-12B, and D-11B, which are more fine-grained and beds D-15B through D-18B, which are more coarse-grained. The final six rhythmite beds range from 6  $\phi$  (0.016 mm) to near 7  $\phi$  (0.0078 mm), or fine silt.

Inclusive Graphic Standard Deviation results range from a minimum of  $\pm 0.93 \phi$  in bed D-22B to a maximum of  $\pm 2.23 \phi$  in bed D-2B. Using the standards of sorting indicated in Folk (1974) for Inclusive Graphic Standard Deviation, the majority of the rhythmite beds are poorly sorted to very poorly sorted. The exception to this is in the coarser grained beds (D-14B through D-18B) in the central section of the exposure, which are moderately well sorted to poorly sorted.

**Table 2. Summary of particle size results from Dayton rhythmites.**

Bed	Particle Size			Graphic Mean		Incl. Graph. Stan. Dev.	Sorting*	Skewness	Skew**
	% Sand	% Silt	% Clay	( $\phi$ )	(mm)				
D-1B	7.7	71.4	20.9	6.87	0.0088	2.08	vps	0.07	n.sym.
D-2B	14.4	68.1	17.4	6.42	0.0118	2.23	vps	0.21	fs
D-3B	4.6	80.5	14.9	6.90	0.0086	1.77	ps	0.18	fs
D-4B	6.5	76.5	17.0	6.90	0.0086	1.92	ps	0.15	fs
D-5B	11.1	79.4	9.5	6.37	0.0122	1.81	ps	-0.23	cs
D-6B	3.9	88.0	8.1	6.18	0.0141	1.59	ps	0.26	fs
D-7B	22.7	72.0	5.3	4.93	0.0328	1.47	ps	0.32	sfs
D-8B	13.9	78.4	7.7	5.47	0.0222	1.68	ps	0.32	sfs
D-9B	7.4	86.9	5.8	5.27	0.0261	1.31	ps	0.34	sfs
D-10B	15.2	78.5	6.3	5.10	0.0295	1.47	ps	0.31	sfs
D-11B	2.4	88.7	8.8	5.92	0.0165	1.49	ps	0.33	sfs
D-12B	2.5	91.5	5.9	5.98	0.0160	1.34	ps	0.36	sfs
D-13B	8.7	89.2	2.0	5.23	0.0265	1.13	ps	0.24	fs
D-14B	9.7	88.2	2.1	5.07	0.0298	0.96	ms	0.18	fs
D-15B	20.2	75.6	4.1	4.88	0.0342	1.23	ps	0.18	fs
D-16B	20.7	77.1	2.1	4.78	0.0365	1.03	ps	0.23	fs
D-17B	33.0	64.8	2.1	4.63	0.0410	1.07	ps	0.41	sfs
D-18B	30.7	67.1	2.2	4.77	0.0366	1.14	ps	0.32	sfs
D-19B	10.6	87.1	2.3	5.25	0.0263	1.18	ps	0.15	fs
D-20B	9.4	88.5	2.1	5.17	0.0282	1.16	ps	0.20	fs
D-21B	13.4	85.1	1.5	5.02	0.0310	1.11	ps	0.28	fs
D-22B	20.0	77.9	2.1	4.77	0.0366	0.93	ms	0.12	fs
D-23B	7.3	91.2	1.5	5.37	0.0242	0.96	ms	-0.04	n.sym.
D-24B	5.0	85.4	9.6	6.52	0.0110	1.67	ps	0.21	fs
D-25B	4.7	94.3	1.0	5.35	0.0248	0.96	ms	0.00	sym.
D-26B	24.1	74.9	1.0	4.95	0.0325	1.23	ps	0.08	n.sym.
D-27B	11.0	88.0	1.0	5.17	0.0282	1.03	ps	0.05	n.sym.
D-28B	18.2	79.6	2.2	4.97	0.0318	1.23	ps	0.18	fs
D-29B	5.8	90.8	3.4	6.05	0.0151	1.26	ps	0.26	fs
D-30B	4.5	84.8	10.7	6.57	0.0105	1.66	ps	0.17	fs
D-1T	16.9	75.1	8.0	6.00	0.0156	2.01	vps	0.00	sym.
D-5T	5.5	83.9	10.6	6.72	0.0096	1.66	ps	0.14	fs
D-15T	7.5	82.1	10.5	6.80	0.0093	1.70	ps	0.03	n.sym.
D-22T	6.3	83.3	10.4	6.87	0.0088	1.70	ps	0.03	n.sym.
D-30T	10.4	79.7	9.8	6.37	0.0122	1.86	ps	0.18	fs

\* vps = very poorly sorted, ps = poorly sorted, ms = moderately sorted  
\*\*sfs = strongly fine skewed, fs = fine-skewed, (n.)sym. = (near) symmetrical, cs = coarse-skewed

Skewness measurements range from -0.23 to +0.41. This indicates that the sediments are generally fine-skewed to strongly fine skewed. The exceptions to this are beds D-1B, D-2B, D-23, and beds D-25B through D-27B, which are near symmetrical to symmetrical, and beds D-5B and D-23B, which are coarse skewed.

As anticipated, the results from the five upper (relatively fine-grained) sections of rhythmite beds at Dayton show little variation. The beds studied were D-1T, D-5T, D-15T, D-22T, and D-30T. Mean particle size ranges from 6.00  $\phi$  (0.016 mm) to 6.87  $\phi$  (0.0088 mm), but three of the samples are within 0.15  $\phi$  of each other (D-5T, D-15T, and

D-22T). Only D-1T (the last flood event recorded) and D-30T (the first flood event recorded) have slightly larger mean particle size. It is believed that sampling error may have occurred in these two samples, the one (D-1T) located in thick vegetation at the top of the slope, and the other (D-30T) located at the base of the slope and partially covered by colluvium from the landslide. All top rhythmite bed samples register as poorly to very poorly sorted with Inclusive Graphic Standard Deviation results of  $\pm 2.01 \phi$  to  $\pm 1.66 \phi$ . All rhythmite top samples have a skew that is near symmetrical to fine skewed. The weight percent and cumulative weight percent graphs (Appendix A) for these samples appear very similar to each other. The overall graphical distribution curves for the rhythmite top samples are much more widely and evenly distributed than their counterpart graphs of the rhythmite bottom samples, which tend to be sharply peaked around the mean grain size.

### Greeley Avenue Site

At the Greeley Avenue site, the lower to middle rhythmite beds consist of basalt-rich, medium to coarse sands and gravels in the bottom sections of the rhythmite couplets, with medium to fine silty sands in the top sections. The upper sequences generally consist of coarse to medium sands in the bottom sections of the rhythmite couplets, topped with medium to fine sands and coarse to medium silts. The uppermost sections of the rhythmite beds, near the top of the bluff, appear to have an almost clay-like fineness. However, based on the particle size analyses performed on the Dayton

deposits, it is estimated that the mean particle size to be found in the upper sections of the top rhythmites at Greeley Avenue is probably in the fine to medium-fine silt range.

Between the two general trends in rhythmite bed character at the Greeley Avenue site is bed G-15, an anomalously thick and coarse-grained sequence (Fig. 13). This thick bed (4.13 m) is almost entirely composed of very poorly sorted and massive coarse gravels, pebbles, cobbles, and small boulders up to 45 cm in diameter. The upper, “fine”, layer of this interval is only 0.03 m thick and consists of fine sand and silt. This sequence is indicative of a high-energy environment of deposition and must represent a truly huge event, even among the Missoula Floods.

Another anomalously thick and coarse sequence is found nearer the top of the bluff in bed G-7 (Fig. 18). This couplet bed is 3.02 m thick. The lower section of this rhythmite bed consists of medium sands (2.97 m) overlain by medium to fine sands and coarse silts (0.05 m). Bed G-7 is interesting as well for the presence of a clastic dike trending approximately vertically through the entire thickness of the bed. The dike is approximately 10 cm wide at the top, where the overlying rhythmite bed truncates it. The dike pinches gradually downward toward the bottom to a width of only 1 cm just before the bounding sides come together as it trends into the slope. Sediments within the dike are noticeably different from those in the surrounding bed, being distinctly lighter colored and finer-grained. Interior sediments appeared to be mostly fine sands, with an approximately 3 mm thick “rind” along the outer edges of the dike of even finer material. This feature appears to be similar in character to clastic dike features recently

studied in the Touchet Beds of southeastern Washington (Silver and Pogue, 2002). Those dikes in the Touchet Beds were interpreted to be created by infilling of fissures produced by seismically induced lateral spreading near a free slope face (Silver and Pogue, 2002).



**Figure 18. Clastic dike in rhythmite bed G-7 at Greeley Avenue.**

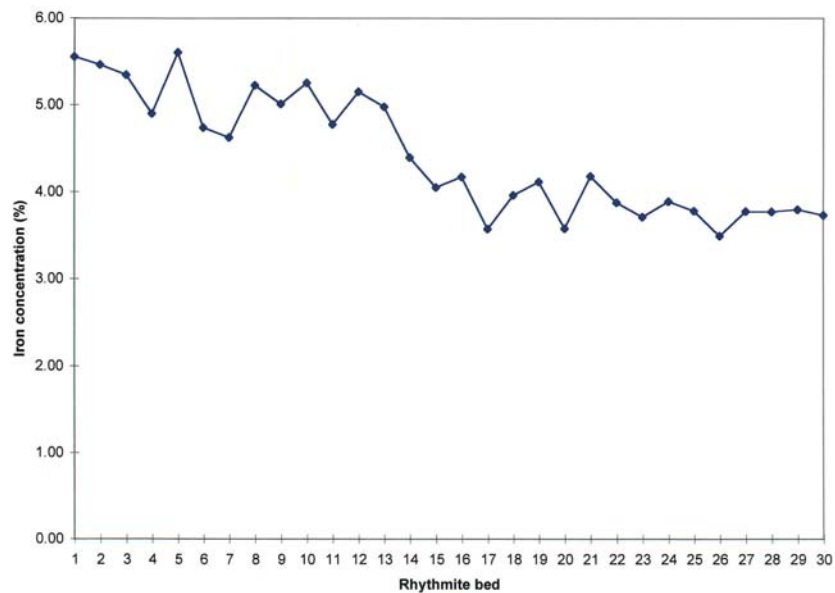
#### *INAA Results*

The sequence of rhythmites at the Dayton exposure exhibits several interesting geochemical trends. Many constituent elements show a distinct transition in concentration and/or concentration trends in the beds directly surrounding D-13 through D-15. Most dramatic and telling are the elements iron, scandium, and chromium.

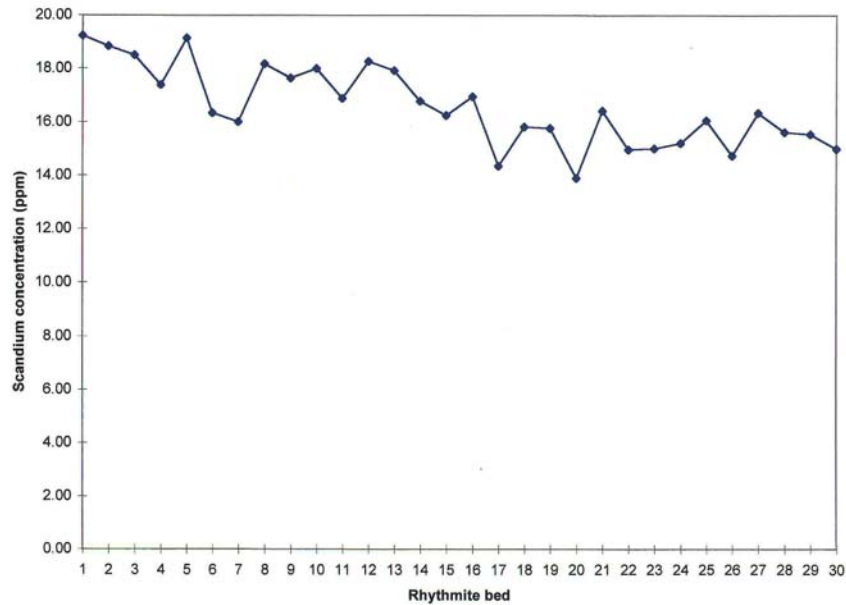
A complete listing of element concentrations for each rhythmite bed at the Dayton site (and selected other reference samples) is given in Appendix B. The elemental concentrations listed in the Appendix B tables are given in parts per million by weight, except for the elements iron, sodium, and potassium, which are in percent by weight. Sigma values (standard deviations) in the table are  $\pm$  the same units as the element in the preceding column. The sample prefixes used in Appendix B are as follows: WW = Walla Walla, Washington exposure (road cut), RI = Ross Island exposure in SE Portland, BR = Portland Hills Silt (Lawes, 1997), BR-CR = Palouse Silt Formation, eastern Washington, CRB ST = a U.S.G.S. geochemical standard for the Columbia River Basalt Group, and D = the Dayton exposure.

Both iron and scandium show a clear increase in concentration through time (from bottom to top) in the rhythmite beds at the Dayton exposure (Figs. 19 and 20). Iron increases from approximately 4 % to approximately 5.5 %, by weight, chronologically (bottom to top), through the stratigraphic sequence. Minimum iron concentration is 3.49 %  $\pm$  0.04 % in beds D-26T and maximum iron concentration is 5.61 %  $\pm$  0.05 % in bed D-5T. Scandium increases from about 15 ppm to about 19 ppm, by weight, over the same stratigraphic interval. Minimum scandium concentration is 13.90 ppm  $\pm$  0.05 ppm in bed D-20T and maximum scandium concentration is 19.25 ppm  $\pm$  0.09 ppm in bed D-1T. The increase in concentration of both of these elements becomes more marked at a transition zone surrounding beds D-15T through D-13T.

The transition zone can be visualized by recognizing that the lower half of the exposure (beds D-14T through D-30T) has concentrations of less than roughly 4 % iron and 17 ppm scandium, respectively, and the upper half of the exposure (beds D-1T through D-13T) has concentrations of greater than roughly 4 % iron and 17 ppm scandium. Iron and scandium also tend to follow each other closely in their bed-to-bed fluctuations. This can be observed by direct comparison of the concentration graphs for iron and scandium.

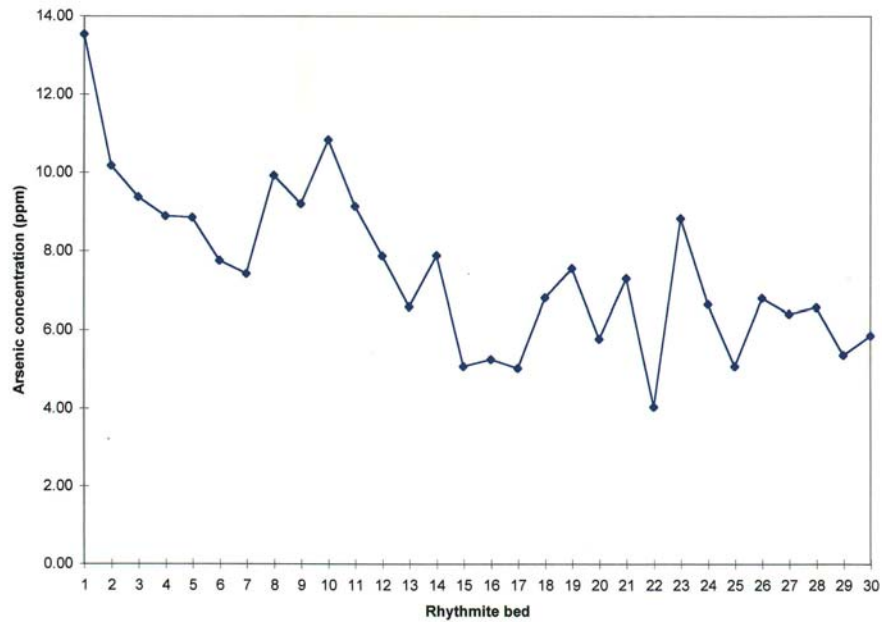


**Figure 19. Iron concentration (%) in Dayton rhythmites.**



**Figure 20. Scandium concentration (ppm) in Dayton rhythmites.**

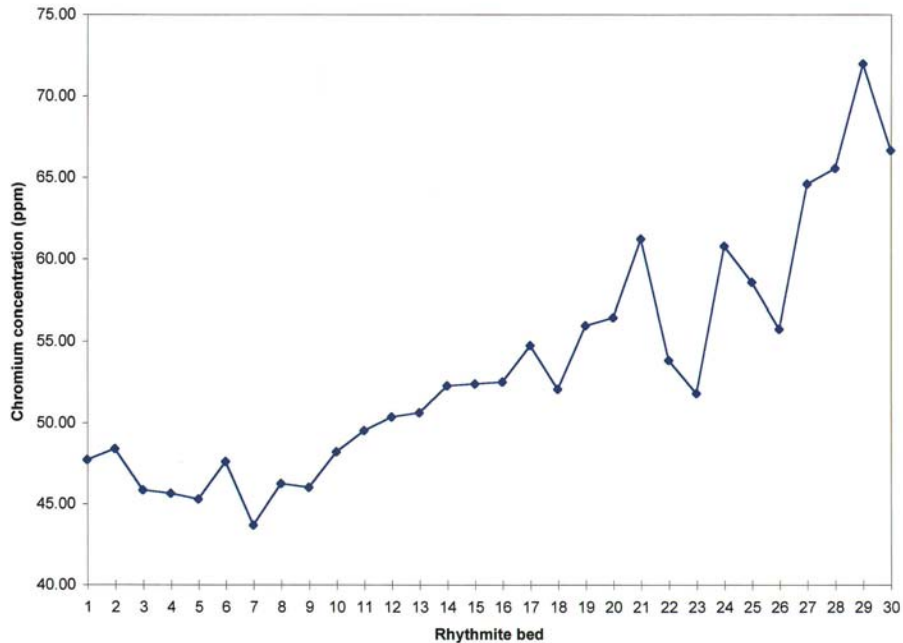
Arsenic also shows an increase in concentration through time, but the trend is more chaotic in the early beds (Fig. 21). The concentration of arsenic jumps dramatically, however, following the transition zone around beds D-15T through D-13T. This rise in arsenic concentration is poorly understood, as it cannot be reconciled with either hypothesized source (glaciogenic Palouse Silt Formation or Columbia River Basalt Group) of the flood sediments (see arsenic results for samples BR-CR1 through 5 and CRB ST 1 in Appendix B). Values of arsenic remain high in the upper (later) flood beds where the floods would have been cutting through basalt. Values should drop because basalt is very low in arsenic content.



**Figure 21. Arsenic concentration (ppm) in Dayton rhythmites.**

Chromium shows a drop in concentration over time from approximately 70 ppm, by weight, in beds D-29 and D-30 to approximately 45 ppm in the upper 5 beds (Fig. 22). Maximum concentration of chromium is  $71.99 \text{ ppm} \pm 1.78 \text{ ppm}$  in bed D-29T and minimum concentration is  $43.72 \text{ ppm} \pm 1.46 \text{ ppm}$  in bed D-7T. This drop in concentration is somewhat attenuated in degree following the transition zone around beds D-15T through D-13T, but generally continues throughout the entire stratigraphic sequence (Fig. 9). As with iron and scandium, this transition can be simplified by recognizing that the lower half of the exposure contains greater than roughly 52 ppm of chromium and the upper half of the exposure contains less than roughly 52 ppm

chromium. The elements lanthanum and thorium show trends similar to that of chromium, though not as pronounced (Appendix B).

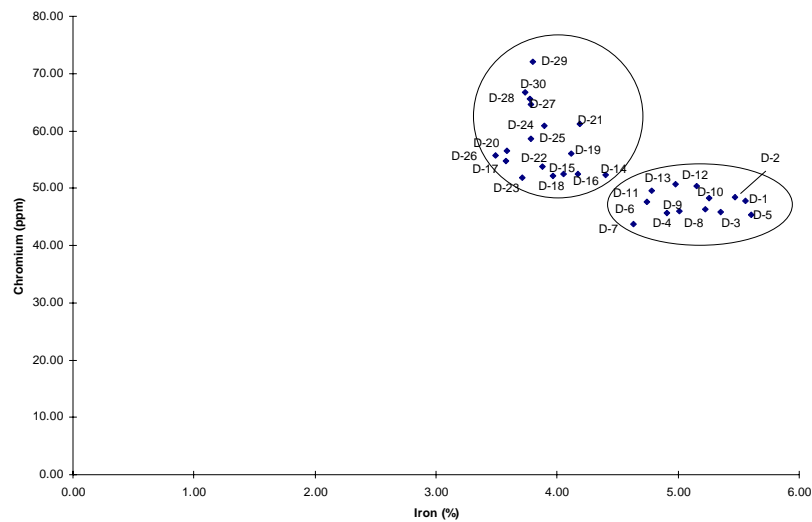


**Figure 22. Chromium concentration in Dayton rhythmites.**

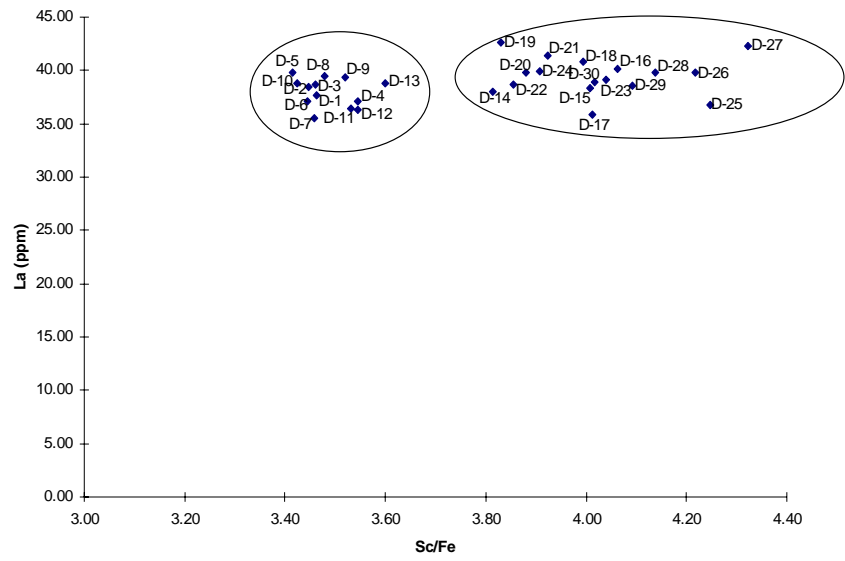
A comparison of the concentration graphs of chromium with those of iron and scandium shows an interesting juxtaposition of trends, crossing near the transition zone in the middle of the Dayton exposure.

Other elements included in the INAA (zirconium, hafnium, tantalum, uranium, sodium, potassium, strontium, barium, rubidium, cesium, zinc, cobalt, antimony, cerium, neodymium, samarium, europium, terbium, ytterbium, and lutetium) showed little or no clear trends in the rhythmite beds at the Dayton exposure.

A comparison of certain elemental concentrations and concentration ratios is a common technique to emphasize sample population differences and similarities (Miyake, 1965; Dr. Marvin Beeson, personal communication, 1997). Such comparisons using the elements iron, scandium, chromium, and lanthanum reveals that the geochemical signatures of the upper and lower halves of the Dayton exposure fall into two distinct, non-overlapping populations - those above the transition zone (beds D-1 through D-13) and those within and below the transition zone (beds D-14 through D-30) (Figs. 23 and 24). This is an unexpected result that has fascinating implications.



**Figure 23. Chromium (ppm) vs. Iron (%) in Dayton rhythmites.**



**Figure 24. Lanthanum (ppm) vs. Scandium/Iron ratio in Dayton rhythmities.**

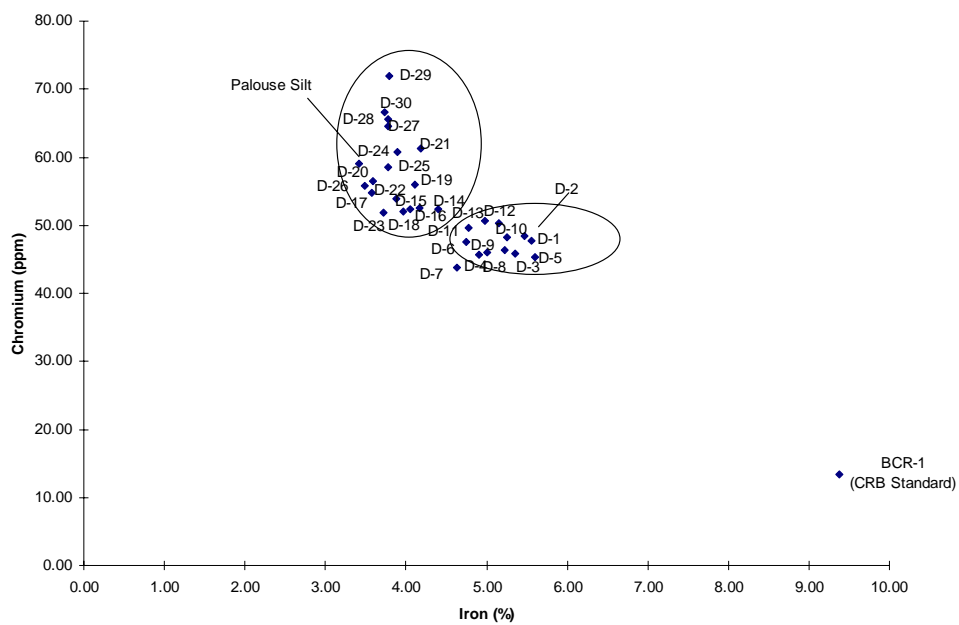
## Chapter 5 - Discussion

Results show that at least 30 Missoula Flood events occurred that were large enough to backfill the Willamette Valley and deposit significant sedimentary packages as far south as Dayton, Oregon. More events may have been recorded at the Greeley Avenue and Dayton sites. The upper and lower stratigraphic contacts of the rhythmite bed sequence were not definitively identified at either of the exposures studied. The bottom of the exposures at both sites is obscured by thick colluvium in the form of landslide debris. A limited number of rhythmites (one to three, based on typical thickness measured) may also be present above the exposures presented, obscured by heavy vegetation and steep slopes, in the near subsurface.

In the rhythmite beds at the Dayton and Greeley Avenue sites, a common and potentially correlative stratigraphy is recognized. Variation in bed thickness and fluctuations in particle size distribution are similar at both sites. At the Dayton exposure, individual rhythmite beds generally become thicker toward the middle of the sequence, then wane following the large event at bed D-15. At both exposures, relatively larger flood events can be interpreted in beds 14 through 18, and 7. It is significant that the largest depositional event in both exposures occurs near the center of the stratigraphic sequence (beds D-15 and G-15). It may be possible to use this maximum thickness bed as a stratigraphic marker in other exposures in the Willamette Valley. It is important to note, however, that the bed numbering used here is an artifice and that it is possible that beds D-15 and G-15 may not be from the same flood event.

The measurement of individual bed thickness and variation in thickness, allowing for recognition of such a marker, has not been discussed in previous works on Missoula Flood sequences elsewhere (Glenn, 1965; Waitt, 1985)

Comparison of the two geochemical groupings found at Dayton superimposed over values for the Palouse Silt Formation of eastern Washington State (Lawes, 1997) and BCR-1, a U.S.G.S. geochemical standard for the Columbia River Basalt Group (CRBG), show a clear implication (Fig. 25).



**Figure 25. Chromium (ppm) vs. Iron (%) showing relation to the Palouse Silt Formation and Columbia River Basalt Group.**

The Palouse Silt Formation and its equivalent deposits would have been the initial source sediments available for transport to the early Missoula Flood events. The genetic origin of the Palouse Silt Formation is as glacial outwash and associated loess from the glaciated plutonic and metamorphic terranes of northern Idaho, Montana, and the western Canadian Shield (Bjornstadt, 1980). These deposits covered much of eastern Washington prior to the Missoula Floods. The CRBG is the bedrock for the same area over which the floods surged.

The lower (earlier) beds at Dayton plot closely, chemically, to the Palouse Silt Formation of eastern Washington, to upper bed outcrops of Missoula Flood deposits near Walla Walla, and to the Portland Hills Silt Formation (also of Palouse Silt-Columbia River floodplain origin, but eolian in nature) (Lawes, 1997; Percy et al., 1998; James et al. 1998). This both implies that the silt soils of the ancestral Palouse plains are the initial source material for the Missoula Flood deposits and establishes provenance for the rhythmites found within the Willamette Valley. That the sediment source of the earlier Willamette Valley rhythmites is the washed away silts of the glaciogenic ancestral Palouse plains can be demonstrated by the high initial values (in the lower rhythmite beds) of chromium and lanthanum, diagnostic of plutonic minerals such as hornblende and pyroxenes and their associated metamorphic and sedimentary by-products (Miyake, 1965). High initial values in the lower beds of the exposure of other elements also support this plutonic primary origin, among them thorium, rubidium, cesium, antimony and, neodymium (Miyake, 1965) (Appendix B).

The beds following the transition zone (beds D-13 to D-1) seem to have a significant influence of CRBG as seen from the pulling of the chemical composition toward that end member of source area composition. An increased basaltic influence can be seen in the increase of iron and scandium (Dr. Marvin Beeson, 1997, personal communication) toward the upper section of the rhythmites. Calculations done using elemental abundances found in the Dayton section and typical elemental abundances found in the Palouse Silt Formation and CRBG (as hypothetical end members) show an increase of basaltic material from an initial 10% to approximately 50% in the rhythmite sediments through time. This change occurs most prominently in the region approximately above and below the transition zone surrounding beds D-13 through D-15.

This evidence would suggest that at some time toward the middle of the flood sequence, represented by the transition zone, these cataclysmic floods were able to scour all the way through the thick loessal topsoil of eastern Washington. The floods then began to carve into the weathered soils and bedrock of the CRBG in earnest, forming the dramatic coulee cataracts and the Dry Falls of the Channeled Scabland.

This idea is reinforced by the fining of the mean particle size found in the sediments in the upper rhythmite beds. This trend toward finer-grained sediment may represent an increased fraction in the beds of the more clay-rich, weathered basalt soils of the CRBG, as opposed to the quartzo-feldspathic glaciogenic silts of the ancestral Palouse plains.

The increased clay-sized content in the earliest flood bed (D-30B) (11 %) and in the last four flood beds (D-4B through D-1B) (17 % to 21 %) analyzed at the Dayton site may be independent of the change in the character of sediments available in the source area. It is possible that the increased clay-sized content in these few beds may be related to normal weathering of the upper source sediments, in the case of bed D-30B, and the continued weathering of the more CRBG-influenced and clay-rich Willamette Valley surface deposits (the upper rhythmites) in the time interval between the last of the Missoula Flood events and the present in the case of beds D-4B through D-1B.

The evidence supports the idea that a substantial number of floods were required for the removal of the thick layer of glaciogenic and loessal Palouse Silt Formation soils. When this thick package of glacial outwash derived soil was finally penetrated, and the floods began to carve into the Miocene soils and bedrock, the chemistry and sedimentology of the deposited flood rhythmites in the Willamette Valley reflected this change in character of the source materials.

The change in character of the sediments transported from the source region could also explain the change in the physical stratigraphy observed at the Dayton and Greeley Avenue sites. The thinning of the beds following the transition zone could be a reflection of the final removal of easily erodable material from the source region. The deposits toward the end of the flood sequence may reflect a relative sediment starvation effect as the deep bedrock channels were established and easily erodable sediments were depleted. Available sediment for transport would be restricted to bank topples, entrained

sediments of Glacial Lake Missoula, and glacio-fluvial and eolian input from the braided outwash drainages that continued to flow from the ice sheets to the north during the interim periods between floods. The geochemical evidence presented here makes likely this possibility for the relative thinning of the upper beds of Missoula Flood rhythmite sequences observed in widely spaced locations.

Another possible explanation for the variation in bed thickness in the stratigraphy of the rhythmite beds seen at both of the study sites may be related to climatic fluctuations during the time period when the floods were occurring. It is possible that variations in climate produced relative glacial maxima just prior to the larger flood events. This could have led to heightened glacial surges at the location of the ice dam to Glacial Lake Missoula. This could in turn lead to increased ice dam height, a longer period of build up prior to the next breaching, and an increased volume of water available to the subsequent flood event.

## Chapter 6 - Conclusions

Results of this study show that at least 30 catastrophic flood events are represented in the sediments found at two exposures in the Willamette Valley. These exposures are located at Greeley Avenue in North Portland at the western edge of Alameda Ridge, and near the town of Dayton, Oregon, approximately 40 kilometers to the south-southwest.

Stratigraphic and sedimentological evidence suggests that Missoula Flood events generally grew in force and volume to a maximum at the time of deposition represented by the central beds (D-15 and G-15) of the exposures under scrutiny. The magnitude of the floods then waned, with the exception of another relatively large event represented near the top of both measured exposures (beds D-7 and G-7).

### *Greeley Avenue Site*

Rhythmite beds at the Greeley Avenue site in north Portland range in thickness from 0.07 m to 4.13 m. Most beds are between 0.5 m and 1 m with an average of  $0.91 \text{ m} \pm 0.94 \text{ m}$ . The thickest rhythmite bed at Greeley Avenue (designated bed G-15) is 4.13 m thick and is located roughly in the center of the exposure.

Rhythmite bed top sections at Greeley Avenue average  $0.14 \text{ m} \pm 0.20 \text{ m}$  in thickness. Rhythmite bed bottom sections at Greeley Avenue average  $0.77 \text{ m} \pm 0.92 \text{ m}$ .

A clastic dike was observed at the Greeley Avenue site, in bed G-7, similar in character to dikes described in the Touchet Beds of eastern Washington (Silver and Pogue, 2002).

### *Dayton Site*

Rhythmite couplet beds at the Dayton site in Yamhill County range in thickness from 0.28 m to 0.97 m. Beds at the Dayton site generally increase to a maximum size toward the middle of the exposure (bed D-15) and decrease again in size toward the top. The thickest rhythmite bed at Dayton is the 0.97 m thick bed, designated bed D-15, located roughly in the center of the exposure.

Rhythmite bed top sections at Dayton average  $0.10 \text{ m} \pm 0.04 \text{ m}$ . Rhythmite bed bottom sections at Dayton average  $0.39 \text{ m} \pm 0.17 \text{ m}$ .

Whole rhythmite couplet bed thickness at Dayton averages  $0.49 \pm 0.18 \text{ m}$ . Average thickness of the rhythmite couplets in beds D-1 through D-13 is  $0.34 \text{ m} \pm 0.06 \text{ m}$ , and average thickness of the couplets in beds D-14 through D-30 is  $0.60 \text{ m} \pm 0.15 \text{ m}$ . The lower beds, in other words, are approximately twice as thick as the upper beds on average.

### *Particle Size Analysis*

Sieve and pipette analysis of the rhythmite bottom sections at Dayton, Oregon, give Inclusive Graphic Mean results ranging from a minimum of  $6.90 \phi$  ( $0.0086 \text{ mm}$ )  $\pm 1.77 \phi$  in bed D-3B and  $6.90 \phi$  ( $0.0086 \text{ mm}$ )  $\pm 1.92 \phi$  in bed D-4B to a maximum of  $4.63 \phi$  ( $0.041 \text{ mm}$ )  $\pm 1.07 \phi$  in bed D-17B. Inclusive Graphic Standard Deviation ranges

from  $\pm 0.93 \phi$  (indicating moderately well sorted) in bed D-22B to  $\pm 2.23 \phi$  (indicating very poorly sorted) in bed D-2B. Skewness measurements for the rhythmite bottom sections at Dayton range from  $-0.23$  (indicating coarse-skewed) in bed D-5B to  $+0.41$  (indicating strongly fine-skewed) in bed D-17B.

Sieve and pipette results of five selected rhythmite top sections at Dayton give a range of Inclusive Graphic Mean from  $6.00 \phi$  (0.0156 mm)  $\pm 2.01 \phi$  to  $6.87 \phi$  (0.0088 mm)  $\pm 1.70 \phi$ . Inclusive Graphic Standard Deviation ranges from  $\pm 1.66 \phi$  (indicating poorly sorted) in bed D-5T to  $\pm 2.01 \phi$  (indicating very poorly sorted) in bed D-1T. Skew of the rhythmite top sections ranges from 0.00 (indicating symmetrical distribution) in bed D-1T to  $+0.18$  (indicating fine-skewed) in bed D-30T.

#### *INAA*

Chemical abundances of the elements iron, scandium, and arsenic show an increase through time in the stratigraphic sequence at Dayton. Iron concentration increases from a minimum of  $3.49 \% \pm 0.04 \%$  in bed D-26T to a maximum of  $5.61 \% \pm 0.05 \%$  in bed D-5T. Beds D-1T through D-13T all show iron concentrations of greater than 4 % and beds D-14T through D-30T all show iron concentrations of less than 4 %. Scandium concentration increases from a minimum of  $13.90 \text{ ppm} \pm 0.05 \text{ ppm}$  in bed D-20T to a maximum of  $19.25 \pm 0.09 \text{ ppm}$  in bed D-30T. Beds D-1T through D-13T all show scandium concentrations of greater than 17 ppm and beds D-14T through D-30T all show scandium concentrations of less than 17 ppm. Arsenic increases from a

minimum of 4.04 ppm  $\pm$  0.94 ppm in bed D-22T to a maximum of 13.54 ppm  $\pm$  0.82 ppm in bed D-1T, an unexpected result that is poorly understood.

Chromium shows a decrease in concentration over time through the stratigraphic sequence at Dayton. Concentration decreases from a maximum of 71.99 ppm  $\pm$  1.78 ppm in bed D-29T to a minimum of 43.72 ppm  $\pm$  1.46 ppm in bed D-7T. Beds D-1T through D-13T all show chromium concentrations of less than 52 ppm and beds D-14T through D-30T all show chromium concentrations of greater than 52 ppm.

It may be possible to use these chemical concentration trends and limiting values (i.e. 4 % for iron, 17 ppm for scandium, and 52 ppm for chromium) as a tool to predict stratigraphic position of a rhythmite bed from a more limited exposure. It may also be possible to correlate stratigraphic exposures across the Willamette, Yamhill, and Tualatin Valleys and the Portland Basin based on these INAA concentration guidelines.

The inverse relationship of concentrations of iron and scandium to chromium through time can be interpreted as a change in the available source area sediment from the plutonic and metamorphic derived glaciogenic loess soils to the underlying weathered basalt soils of the Columbia River Basalt Group bedrock. Calculations show that there is an increase in basaltic content in the Dayton beds from approximately 10 % to 50 % through time, with the change showing most prominently in the transition zone around beds D-15T through D-13T.

Geochemical and sedimentological evidence suggests that the largest Missoula Flood events, represented in rhythmite beds near the center of the Willamette Valley

exposures, may be interpreted to indicate the final removal of more easily erodable glaciogenic loess from the source region. Flood beds deposited after this event record an increased content of fine-grained and basaltic material. This may represent the establishment of well-defined flood paths in the Channeled Scabland terrain in eastern Washington State.

Changes in stratigraphic thickness of individual flood event rhythmite beds may be tied to climatic fluctuations and corresponding variations in the size of the ice dam impounding Glacial Lake Missoula at the time of the floods.

## Chapter 7 - Future Work

Questions raised during the course of this work promote the need for additional studies including the following:

- Trenching of the Greeley Avenue and Dayton sites to determine the lower stratigraphic contacts and to establish definitively exactly how many floods are represented.
- Trenching and clearing for a full stratigraphic study of the Ross Island exposure, for correlation and comparison to Greeley Avenue.
- Detailed stratigraphic and sedimentologic studies of other known Missoula Flood deposits for potential correlation to the deposits in this study.
- Application of detailed (bed by bed) INAA to other known Missoula Flood deposits (i.e. Touchet Beds, etc.) for potential correlation to the deposits in this study.
- Sampling of the bedrock in different flood pathways (such as the Palouse-Cheney scabland and Grand Coulee, etc.) for comparative INAA analysis to potentially determine flood path history.
- Radiocarbon dating of organic material found in the deposits at Dayton (in progress at this time).

- A more extensive search for clastic dike features in the deposits in the Willamette Valley for comparison to those in other known exposures elsewhere (i.e. the Touchet Beds).

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## **Appendix A - Particle Size Analysis Results**







































































## **Appendix B - INAA Results**













