1991

Erosion of fractured banks, Lake Sakakawea, western North Dakota

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EROSION OF FRACTURED BANKS, LAKE SAKAKAWEA, WESTERN NORTH DAKOTA

by

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Bachelor of Science, University of Minnesota-Duluth, 1987

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Masters of Science

Grand Forks, North Dakota
August
1991

This thesis, submitted by Mark C. Elliott in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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Department Geology and Geological Engineering

Degree Masters of Science

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ACKNOWLEDGEMENTS

I would like to express sincere appreciation to my thesis committee members, Dr. John Reid, Dr. Philip Gerla, and Dr. Richard LeFever. The assistance and constructive criticism they have offered during this project have been invaluable. I am also grateful to them for the time they have taken to review this thesis.

I especially thank my committee chairman Dr. John Reid for giving me the opportunity to become involved with this project. I am fortunate to have had this chance to work with him; he is an outstanding advisor and teacher. I am indebted to him for his constant encouragement, the many hours he devoted to editing this thesis, and for taking the time to discuss this and other research with me. He has helped me become a better scientist and writer.

I would also like to thank Mike Brown and Roberta Barber for their assistance with field work. I appreciate their willingness to endure long hours of work, usually performed in inclement weather. It would have been difficult to complete much of the necessary field work without their assistance.

Finally, I would like to acknowledge the U.S. Army Corps of Engineers, Omaha District Office, the University of North Dakota Mining and Mineral Resource Research Institute, and the University of North Dakota Department of Geology and Geological Engineering for partial funding of this project.

ABSTRACT

Shoreline erosion at Lake Sakakawea has exceeded originally predicted rates. This thesis is a continuation of a project, begun in 1983, to study erosion rates, causes, and prediction; the purpose has been to describe variations in fracture patterns in shoreline banks and assess their affects on erosion rates.

During the first phase of this project (1983-1986), average bank recession was rapid (1.5m/yr) and factors related to wave action, including fetch, bank orientation, and beach composition, were most important. Since 1986, low lake levels have persisted and wave action has not been a factor; however banks continue to recede, but at a slower rate (0.2m/yr), and bank properties, including fracture patterns, height, slope, and composition have become more important. Banks are not yet stabilizing, and factors related to lake levels, wave action, and bank properties must all be considered in predicting future bank recession rates.

Fracture patterns were described at each erosion station. The fractures result from regional stresses related to crustal uplift and NE-SW plate motion, stress release associated with vertical and lateral unloading, subglacial deformation, and/or desiccation. Differences in average fracture size and abundance correspond to changes in lithology. Vertical fractures are smaller and more closely spaced where strong horizontal bedding or fracturing exists. Size and abundance are also affected by grain size, consolidation, weathering.

Consistently oriented N-S, E-W, NE-SW, and NW-SE orthogonal sets of straight, vertical fractures with matte surfaces are dominant in the Paleocene bedrock. Horizontal fracturing also occurs where bedding is

well-developed; it is especially intense in and near lignite layers. The Upper Medicine Hill till contains sets of short, straight, vertical fractures, separated by near-horizontal fractures with straight or curved surfaces; most are sealed with mineral coatings. A columnar jointing pattern in the Upper Snow School and Upper Horseshoe Valley tills results from dominance of orthogonal sets of open vertical fractures with rough surfaces and the absence of horizontal structures.

The most important failure mechanisms affecting these cohesive bank sediments are toppling and high-angle sliding along large vertical bank-parallel tension fractures. Sediments with well-developed horizontal structures are more resistant to this type of failure because the fractures, formed by stress release along the exposed bank, cannot extend as deeply. Thus, Upper Medicine Hill till banks are receding 50% slower than other till banks. Bedrock banks with hard interbedded limestone lenses and strong lithological variations have also receded slower.

Vertical fracture orientations and abundance also affect erosion mechanisms and rates. However, because of the numerous other erosional factors, the multiplicity of fracture sets in the bedrock, and the high dispersion of fracture orientations in some of the tills, it is difficult to correlate these factors directly to variations in erosion rates.

INTRODUCTION

General

Lake Sakakawea is a large man-made reservoir on the Missouri River in western North Dakota (Fig. 1). The area studied includes the eastern end of the lake (Fig. 2). This reservoir was created by the U.S. Army Corps of Engineers (Corps) in 1953 as part of a system to reduce the effects of flooding and to maintain navigation routes on the lower Missouri and Mississippi Rivers. After closure, the water level continued to rise until 1969 when the reservoir first reached its maximum operating level of 564 metres above sea level. Since then, bank erosion, which has been more rapid than originally anticipated, has claimed a substantial amount of land, precipitating land-use management problems surrounding the lake. In fact, by 1979 the Corps determined that at 80% of the sites they were monitoring bank recession had already exceeded ultimate predictions (Cordero, 1982).

This thesis, which is mainly a study of the effects of bank fractures and lake level fluctuation on bank recession rates, is part of a larger project which began in 1983 when the Corps contracted the University of North Dakota to study bank recession rates and processes on Lake Sakakawea. It is hoped that the results of this study will contribute to a better understanding of bank recession processes so that future rates can be predicted more accurately.

In 1983, when this project was initiated, 20 bank recession stations were established so that bank recession rates could be monitored and site-specific geologic and geographic characteristics could be correlated to these rates (Fig. 2). During the initial phases of this project, which

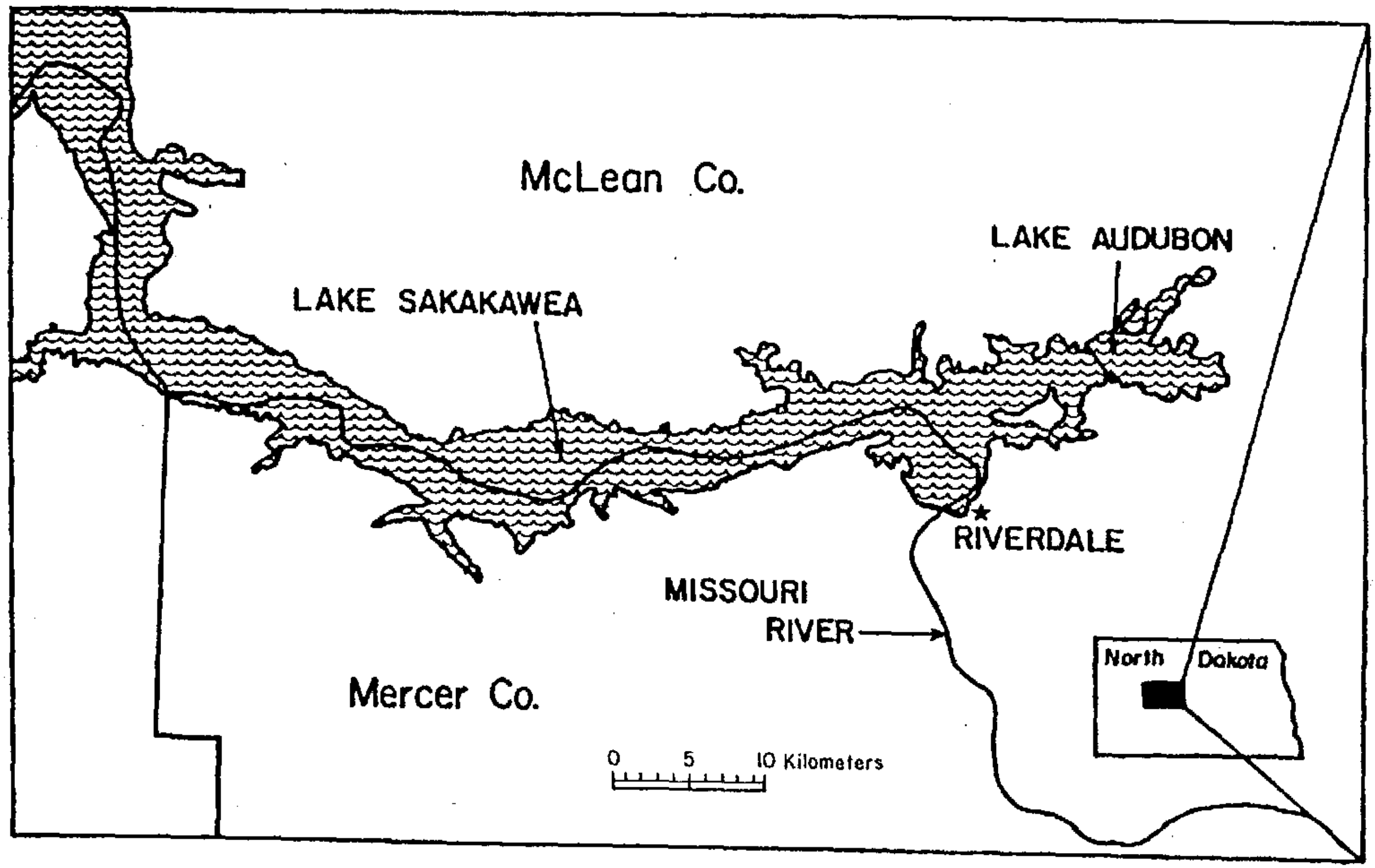
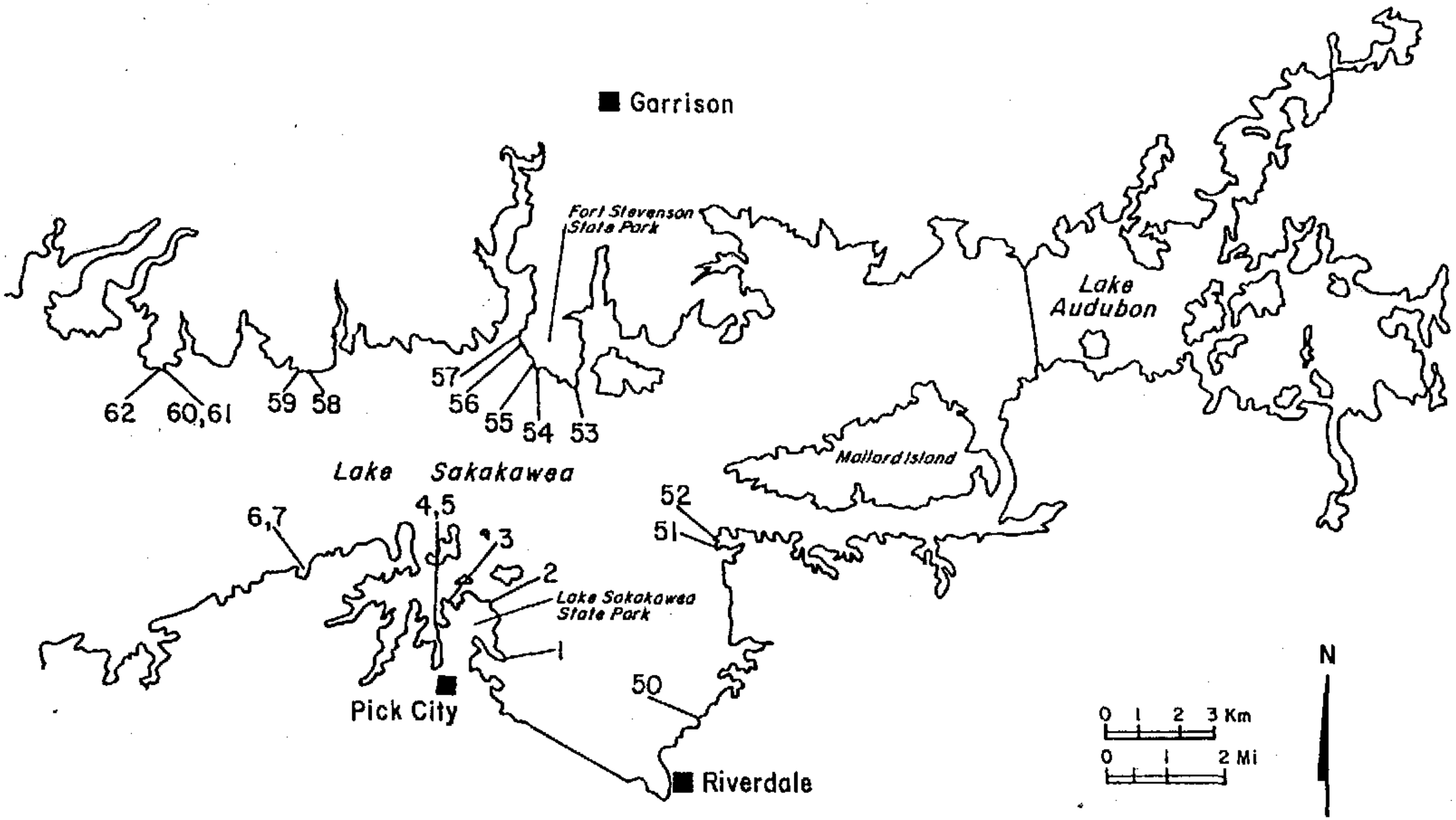


Figure 1. Location Map, Lake Sakakawea, ND.



<u>Figure 2</u>. Study Area and Bank Recession Station Locations.

ended in 1986, wave erosion was the most important erosional process; thus, factors related to wave energy, including effective fetch, bank orientation with respect to the dominant wind direction, beach composition, beach width and slope, and the frequency, duration and direction of storm-driven waves, were recognized as important variables associated with bank recession rates. The importance of wave erosion and related factors during the first three years of this study is attributed to the high lake levels during the summers of 1984, 1986, and briefly in 1983.

Since 1986, lake levels have been too low for direct wave erosion of banks to occur. Nevertheless, these banks, which have been oversteepened due to wave erosion, have continued to recede, but at a slower rate. Bank recession is now mainly the result of bank failure along vertical fracture planes that are weakened and opened by tension due to horizontal unloading and chemical and physical weathering; therefore, during the recent low lake levels, factors such as lithology, bank height and slope, and bank structures, including fractures and bedding, are most important.

Purpose

This thesis involves continuing activities begun during the initial phases of this project, such as monitoring current bank recession rates, assessing the effects of lake level fluctuations and other factors, and estimating trends of future bank erosion rates. The focus, however, was to describe variations in bank fracture patterns and to assess their influence on bank failure mechanisms and bank erosion rates. During earlier phases of this project it was recognized that fractures contributed to decreased bank stability and probably increased short-term bank recession rates at Lake Sakakawea. It was also apparent that fracture patterns varied between sites and among differing lithologies. This study was undertaken to investigate these fractures, including their origin, factors controlling their formation and characteristics, and their influence on bank stability and short-term recession rates.

Slope stability is strongly influenced by the presence of fractures and characteristics such as orientation of sets, length, density, and resistance to failure. Failure of slopes composed of fine-grained sediments and consolidated materials often occurs as intact blocks bounded by fractures break away from steep bank surfaces. Most of the bank recession at Lake Sakakawea can be attributed to this type of failure.

The most important fracture characteristic with regard to slope stability is the orientation of fracture sets. For example, McGown and others (1974) attributed slope failure at excavations in a till near Hurlford, England to the presence of vertical fractures. Excavations that were parallel to vertical fracture sets were prone to shallow failures which initiated along fracture planes. No failure occurred in excavations not oriented parallel to these vertical fracture sets. At Lake Sakakawea most of the bank fractures are nearly horizontal or nearly vertical, and at all of the sites studied there were two to four vertical fracture sets present.

This study is also intended to investigate factors controlling variations in fracture patterns. Differences in average size and density of fractures, the distribution of fracture orientations, and their surface characteristics are related mainly to fracture-forming processes, lithology, and changes in topography. It is important to understand how these factors affect variations in fracture patterns so that meaningful interpretations of the fracture data can be made and the probable fracture patterns at other locations around the lake can be inferred. For example, it is desirable to know whether fracture patterns are consistent throughout the entire region, or if they vary locally with changes in topography, lithology, or weathering history. It is also important to understand what types of variations in fracture patterns to expect between differing lithologies and what variations to expect in a similar lithology at different locations. This requires an understanding of fracture genesis and the area geology, climate, and geological history.

Regional Geology and Climate

The climate in western North Dakota is semi-arid continental with approximately 40 cm of annual precipitation. Although most of the precipitation occurs during the summer, the weather during that season is normally warm and dry and the frequency and abundance of summer rains is sporadic; thus, this region is prone to droughts. Fall and spring are cool with variable precipitation, and winters are cold and dry with precipitation averaging about one centimetre per month. The frost season begins in mid October and normally ends in late April or early May (Millsop, 1985, p. 9).

The surface geology in this area consists mainly of Quaternary glacial sediments deposited directly by moving ice (ground moraine) or deposited during ice stagnation (Fig. 3). These sediments vary in thickness from zero to approximately 100 metres (Bluemle, 1988). Glacial outwash and eolian silt deposits are also exposed locally in this region, and Tertiary bedrock is widely exposed along the shores of Lake Sakakawea. The topography ranges from gently undulating in areas underlain by ground moraine to hilly in areas underlain by stagnation moraines (Bluemle, 1988). The topography of the land within several kilometres of the Missouri river valley has been dissected by stream erosion.

The banks of eastern Lake Sakakawea are 2 to 25 m high and are typically nearly vertical. They consist of Tertiary and Quaternary sediments and sedimentary rocks. The lowest stratigraphic unit in the

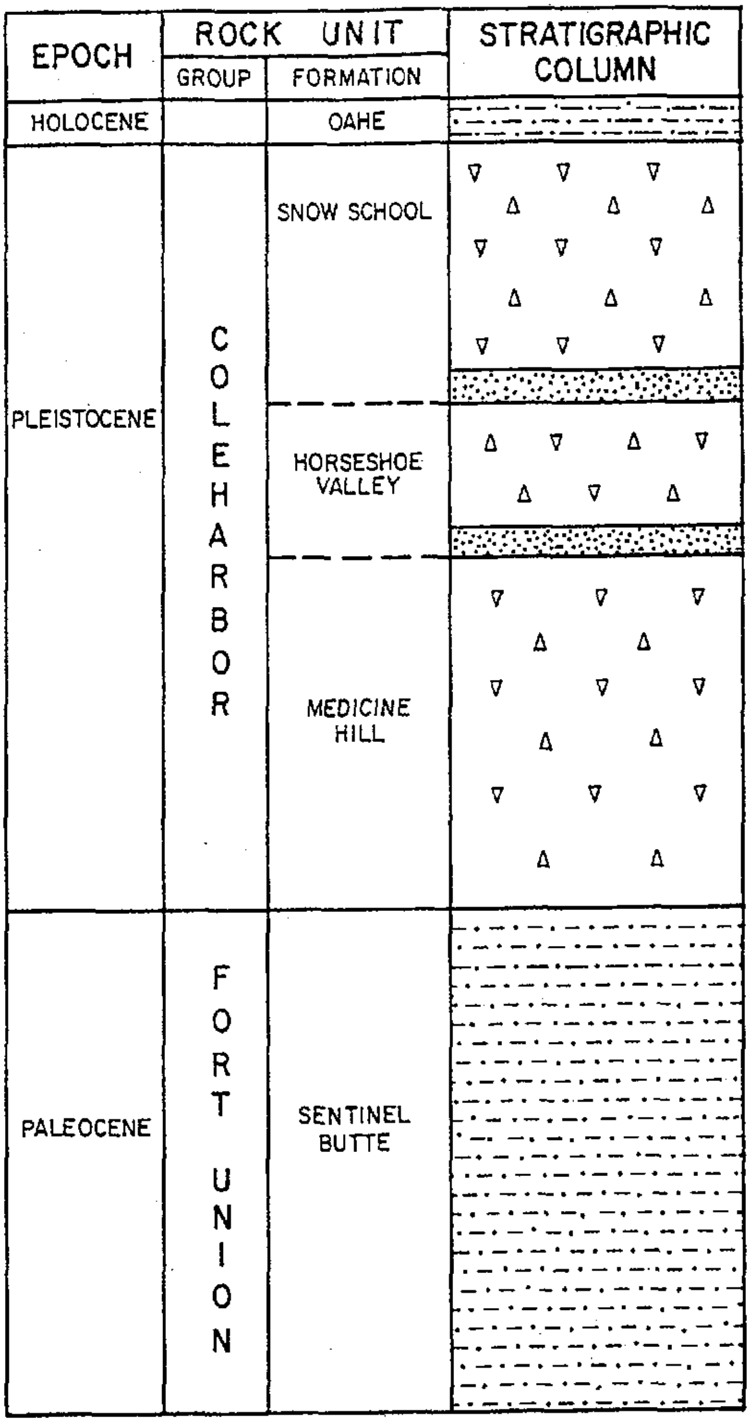


Figure 3. Bank Recession Station Lithologies.

area is the Paleocene Sentinel Butte Formation which consists of interbedded mudstone (ranging from silt to claystone), sandstone, lignite, and clinker (Ulmer and Sackreiter, 1973). This formation is present in the lower portion of many banks, and at a few locations it comprises the entire bank. Glacial sediments of the Pleistocene Coleharbor Group and eolian silt of the Holocene Oahe Formation (Ulmer and Sackreiter, 1973) overlie the Sentinel Butte Formation and comprise the upper portion of the entire bank at many locations. Glacial sediments are the dominant lithology at most of the banks studied.

Definitions

The terms fracture, fissure, and joint are often used interchangeably to describe sediment and rock discontinuities, and they are often given specific meanings that pertain to their origin or appearance. Other terms, such as shear fracture, fault, and joint plane, have also been used to describe specific types of discontinuities. The term fracture is most often used as a general term to describe all structural discontinuities resulting from mechanical failure, while the term joint is most often restricted to rock units that show no displacement across the joint surface (Bates and Jackson, 1980).

Because the terminology pertaining to discontinuities is inconsistent and confusing, it is necessary to define how some of these terms are used in this paper. Terminology proposed by Pollard and Segall (1987) is used in the following manner here: Fracture is a general term referring to all discontinuities regardless of their origin and current characteristics, whereas joint specifically denotes fractures formed by tensile stress. Fractures resulting from differential displacement across a fracture boundary are termed faults. Fracture will be used to identify all discontinuities and joint and fault will be used only when the origin of the fracture has been identified and is being discussed.

Some other terms are fracture set and fracture system. Fracture set refers to a group of nearly parallel fractures and fracture system is used to describe a fracture pattern consisting of more than one set. As an example, the Sentinel Butte Formation usually contains one set of horizontal fractures and two to four sets of vertical fractures oriented 45° or 90° apart. When two sets of vertical fractures are separated by right angles they are referred to as an orthogonal system of vertical fractures.

Previous Work

Bank Recession

The geology of the banks exposed along the eastern end of Lake Sakakawea was first mapped and described by Ulmer and Sackreiter (1973). Earlier, the engineering properties of the Sentinel Butte Formation and some of the glacial tills in the area were tested by Banks (1972), and by the United States Army Corps of Engineers (1981). Also, before this project began in 1983, two studies of shoreline erosion on Lake Sakakawea were conducted by the Corps. One evaluated unsuccessful attempts to predict ultimate bank recession distances by applying a conceptual model based on the conservation of volume (template method) (Cordero, 1982). Another Corps study (Gatto and Doe, 1983), using air photos to estimate bank recession rates from 1958 to 1976, demonstrated the futility of using such methods for measuring bank recession rates accurately.

The template procedure evaluated by Cordero (1982) is based on the assumption that material eroded from a bank will be redeposited in the immediate offshore zone, near the toe of the bank; then, continued accumulation of bank sediment in the offshore zone will eventually result in the formation of a stable offshore platform protecting the bank from further wave erosion (Fig. 4). Because the banks along Lake Sakakawea are composed primarily of fine-grained sediments which are easily transported

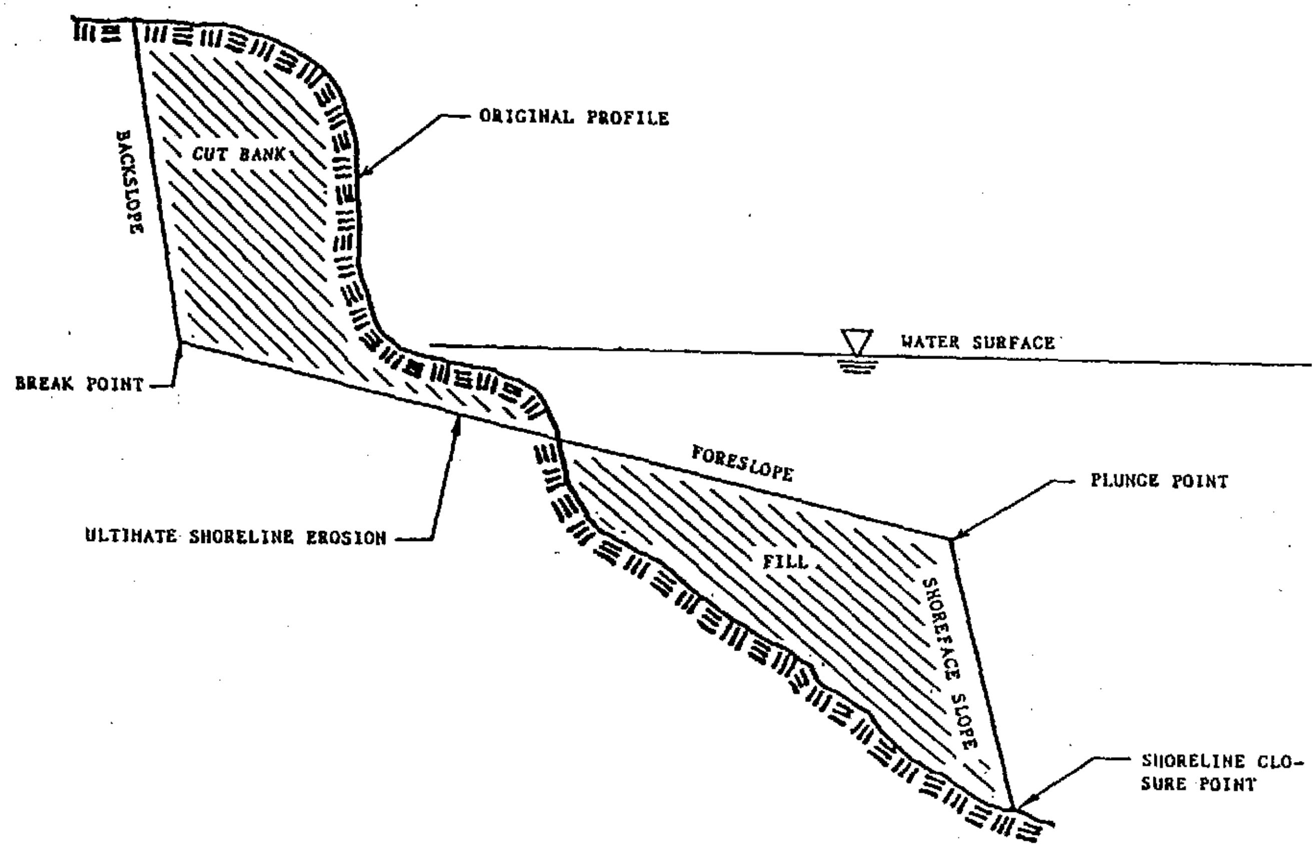


Figure 4. Template Method. Conventional procedure used by U.S. Army Corps of Engineers to predict ultimate shoreline recession (from Cordero, 1982).

to deeper water, this model proved to be inappropriate for this lake. Only 13 years after the maximum pool level had been reached, bank recession had already exceeded the ultimate recession predicted by this model at over 80% of the sites (Cordero, 1982).

With air photos, Gatto and Doe (1983) concluded that the primary cause of "bank recession" from 1958 to 1976 was reservoir inundation and wave erosion. They also attempted to determine the correlation between bank recession rates and other factors, including water level and bank and reservoir characteristics. Because of the small scale of the air photos used, the bank recession measurements made from them were relatively inaccurate and no significant correlations between bank recession rates and factors thought to be associated with bank recession were found.

Millsop (1985) studied bank recession mechanisms, rates, and the controlling geologic factors. He determined that wave action was the primary cause of bank erosion on Lake Sakakawea and the most important factors associated with wave erosion were lake level and wind direction, velocity, and duration. Other important factors were bank orientation, bank geology and geometry, beach composition and geometry, offshore bathymetry, shoreline topography, and the presence of offshore islands (Reid and others, 1988). These studies also indicated that banks shorter than five metres, facing north to northeast, and composed of well-jointed till or mudstone, were receding the fastest.

Sandberg (1986) found that the rate of bank recession from 1983 to 1986 ranged from 0.2 to 4.3 m per year, and that approximately 78% of the bank recession occurred during the warm season months (May-October), primarily from wave erosion. He also concluded that bank recession during the cold season months (November-April) was mainly the result of thaw failure during March and April. In addition, he developed two seasonally-dependent equations for estimating site-specific bank recession rates. These equations were the result of multivarate regression analyses based on data obtained during the first three years of the study. Bank recession rates were used as the dependent variables, and geological factors considered to be closely associated with recession rates, including bank height, effective fetch, offshore slope angle, beach width, mean grain size, percentage of coarse beach clasts, angle between the shoreline and dominant wind direction, and bank orientation with respect to the sun, were tested as independent variables.

Fractures

Although there has been no previous research regarding fracture characteristics of banks along Lake Sakakawea, several studies pertaining to fracture orientations of Tertiary and Quaternary units throughout the region are relevant to this study. Two sets of near-vertical fractures, trending NE-SW and NW-SE, are persistent throughout all types of Cenozoic bedrock and sediments in eastern Montana, western North Dakota and southern Saskatchewan (Erickson, 1970; Stone and Snoeberger, 1977; and Stauffer and Gendzwill, 1986). Both sets are interpreted to be the result of tensile stress associated with vertical uplifting and horizontal movement of the North American Plate (Stauffer, and Gendzwill, 1986). Analyses of fracture characteristics and anisotropic hydraulic properties of coal and related earth materials at the Garrison, Falkirk, Center, and Indian Head coal mines, located near the eastern end of Lake Sakakawea, indicate that these NW-SE and NE-SW fracture sets are dominant in this area also (Rehm and others, 1980).

PROCEDURES

Bank Recession Measurements

Since 1983, bank recession rates at 20 stations along the eastern shores of Lake Sakakawea have been monitored regularly (Fig. 2). These stations were located at sites that were both easily accessible and appeared to be experiencing active bank recession. Most of the stations were located along headlands where relatively rapid bank recession rates were expected, and a few control stations were established in bays where active bank recession is slower.

Each station consists of a series of pins (15 cm-long nails marked with flagging) driven into the ground. The pins are arranged in sets of two, and they are spaced on a line perpendicular to the bank at that point (Fig. 5). The pin farthest from the bank is the reference from which bank recession is measured; an alignment pin is set between this pin and the bank to mark the direction of the measurement line. Currently there is an average of 6 sets of pins at each station (Appendix I).

The amount of bank recession that occurs between measurements at each station is determined using methods employed by Reid and others (1988), where the distances from the pins to the bank edge are measured and compared to distances from the previous measurement (Appendix I).

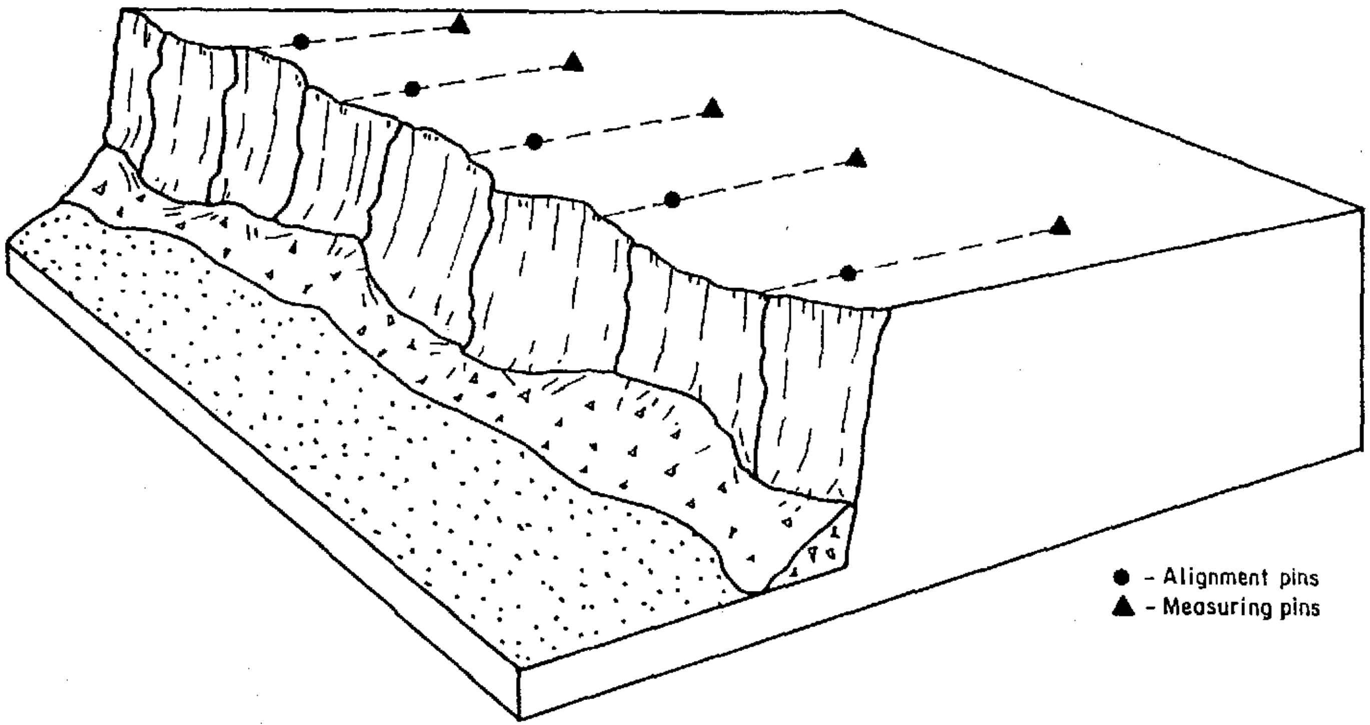


Figure 5. Bank Recession Station showing measurement and alignment pins.

Fractures

Bank-Top Fractures

Ground surface fractures above the bank were described at each station. The descriptions included measurements of orientations, lengths, locations, and aperture widths for bank-top fracture intersected along transects parallel and perpendicular to the bank edges (Appendix IV).

Bank-top fractures, oriented parallel or sub-parallel to the bank edge, were described as bank recession measurements were being taken. Each transect began at the bank edge and extended 8 metres inland. The number of transects at each station coincided with the number of recession pin sets at the station. The orientations of the fracture surface intersections were measured with a compass, and the distances from the bank edge and the aperture widths were measured by taping. Fracture lengths were measured by taping or pacing.

Fractures intersected along transects parallel to the bank edges were also described. This procedure provided a representative number of fractures oriented at a high angle or perpendicular to the bank edge. Each of the four bank-parallel transects extended the length of the station and were spaced at 1, 3, 5, and 8 metres from the bank edge.

Bank-Face Fractures

In addition to the bank-top fractures, bank-face fractures were described. The fresh bank-face exposures provided a clearer and more complete view of bank fractures. Therefore, they were studied more extensively, and the majority of the fracture data analyzed pertain to these fractures.

Orientation: Bank-face fracture orientations were measured by determining the strike and dip of fracture planes. Fracture strike and dip inclinations were determined using a compass and inclinometer. The magnitude of the random error expected for dip angles measured using this technique ranges from 2.9° for high-angle fractures in hard rocks (Ronca and Chaivre, 1977) to 5.0° (Connell, 1984) for low-angle fractures in poorly consolidated sediments. Ronca and Chaivre (1977) also demonstrated that the magnitude of the expected random error for measuring high-angle fracture plane azimuths is approximately 3.2°. The majority of the fractures measured during this study were in fine-grained unconsolidated sediments and were dipping at a high angle. Therefore, the random measurement error associated with these fracture orientations is predicted to be between 3° and 5° for both the strike and dip measurements.

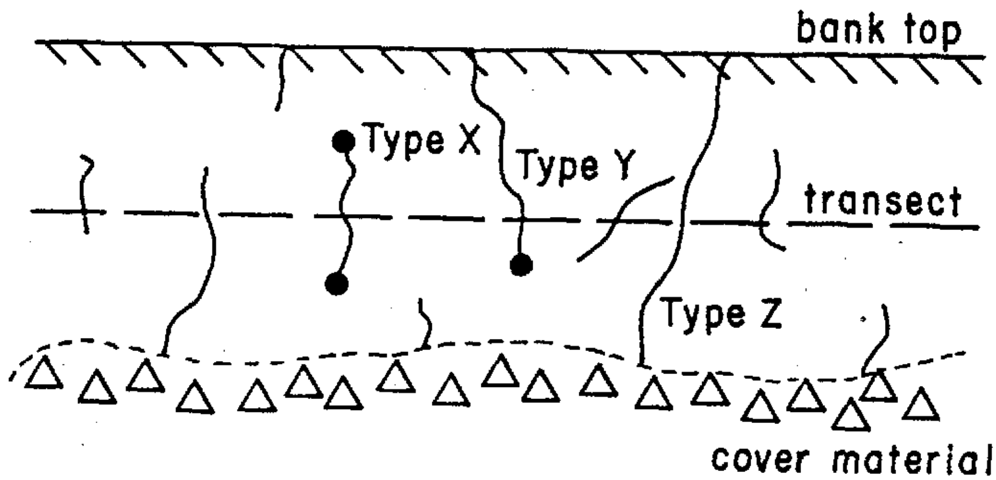
Even though the expected error associated with measuring fractures is small, obtaining a truly representative set of orientations is difficult. The main problem affecting fracture orientation data is bias related to exposure orientation. Obviously, a fewer number of fractures will intersect the exposure from a fracture set oriented at a low-angle to an exposure face than fractures from a set oriented at a high angle to the exposure surface. Because sampling procedures are limited by exposure extent, height, and orientation, completely eliminating this type of bias is difficult. In most situations geologic data must be collected using less than ideal statistical sampling conditions, and often the best way to deal with these difficulties is to recognize the problems and to account for it while conducting analyses and making interpretations.

The fracture orientations were measured for all non-horizontal fractures (fractures inclined at > 10° from horizontal) that intersected the surfaces of approximately rectangular quadrats along the bank faces. Due to inconsistencies related to exposure quality, the size and number of quadrats at each site varied. Sampling bias related to the bank orientation was reduced by sampling exposure faces along at least two different bank orientations at each site. However, because of the limited exposure extent it was not always possible to apply this technique.

Length: The apparent length of fracture traces intersected during the collection of fracture orientation data was also recorded. In addition, a visual estimation was made of the maximum and mean fracture length for each geologic unit at each station. These data were obtained so variations in apparent fracture lengths for each station and geologic unit could be studied and possibly correlated to differences in bank recession rates.

Even though the error associated with measuring lengths of exposed fracture traces is low (Wheeler and Holland, 1981), obtaining representative length data can be difficult when entire trace lengths are not always observable. This is due to the fracture trace extending beyond the exposed area of the outcrop or into another material. When this situation is encountered, the mean fracture length and variance will be less than true values. If one or both ends of a fracture intersection with an exposure are obscured, the fracture length measurement is said to be censored (Fig. 6) (Baecher, 1980). Because longer traces have a greater probability of being censored, these incomplete observations were not ignored. By noting the number of fracture ends visible, corrections were made to the censored data allowing a better estimation of the true mean fracture length to be calculated. After the set of observations is partitioned into groups composed of trace lengths with both ends visible, one end visible, and no ends visible, the distribution of the trace lengths can be derived (Baecher, 1980; Laslett, 1982).

Experimental data indicate that most data sets of fracture lengths have an exponential distribution (Baecher, 1980; Connell, 1984, p.62; and Laslett, 1982). Because of this, and the fact that closed form solutions are easily calculated for this type of distribution, an exponential distribution is usually assumed for fracture lengths (Connell, 1984, p. 63). Examination of fracture length distributions for various lithologies



Type X - fracture traces with both ends visible
Type Y - fracture traces with one end visible
Type Z - fracture traces with no ends visible

Figure 6. Fracture Trace Types.

at Lake Sakakawea (Appendix VII) reveals that assuming a log-normal distribution to determine statistics for these data is a valid approximation.

A procedure for estimating the mean and the variance of log-normal distributed fracture lengths from censored data collected along line transects (Laslett, 1982) was adopted for estimating mean fracture lengths of data sets pertaining to this project. This involved measuring the visible length of each fracture intersected along rectangular horizontal transects. The number of ends visible were also noted so that the technique described by Laslett (1982) could be applied.

The log-normal standard deviations for these data are so small that they are misleading. Because of this the standard deviations reported in the Results section are based on normal distribution statistics and are calculated for the "type X" fractures only. These values are not valid for making statistical inferences; however, they give a more meaningful indication of variations in relative dispersion between data sets.

Another problem regarding measurement of fracture lengths is that surface trace lengths do not represent a three-dimensional view of the true fracture surface size. For example, very long fractures may intersect the bank surface for a relatively short distance. Pollard and Aydin (1988) maintain that when fracture growth is limited in the vertical direction by bedding, the longest dimension of fracture propagation will most likely be parallel to bedding. Thus, the resulting measurement may not be representative of the true size.

This problem should not be ignored when collecting fracture data. However, these data, which represent average vertical fracture trace lengths, are an important bank stability factor. When considering the effects of fracture size on bank stability, the vertical dimension is most important. This is because failure normally occurs along vertical planes which often initiate along vertical fractures.

Fracture Abundance: Vertical and horizontal fracture abundance was estimated for each accessible geologic unit at each of the stations by determining the fracture frequency (Appendix V, VI), this was accomplished by counting the total number of fractures from all fracture sets intersected along vertical and horizontal transect lines.

The number, length, and orientation of the transects needed to accurately determine fracture frequency depends on the average fracture spacing and the orientation of the exposure with respect to fracture set orientations. Because fracture spacing is often variable, transects of at least 50 times the estimated mean fracture spacing, as recommended by Wheeler and Dixon (1980), were used to ensure a more reliable estimation fracture frequency. Also, to reduce bias related to bank orientation, frequencies were measured along at least two nearly orthogonal bank faces at each site. At several sites the limited extent and/or poor accessibility of the exposure made it impossible to collect the desired amount of data (Appendices V, VI).

Geometry and Surface Characteristics: Modification of a scheme for qualitatively describing fracture geometry and surface roughness (Fookes and Denness, 1969) was employed for this project. Fracture surface geometries were characterized as being straight, curved, or irregular, or as possessing a combination of these geometries. Fracture surface roughness was described as either being smooth, matte, or rough. Fracture surfaces with a polished appearance were described as being smooth; even surfaces with a dull, granular, or unpolished appearance were described as being matte; and bumpy irregular surfaces were described as being rough (Appendix III). The presence of surface markings such as pits, plumose structures, and slickensides were also looked for and noted if present. The occurrence and type of mineral coatings on fracture surfaces was also noted (Appendix III).

Detection of a Preferred Orientation

Directional variations of strength are influenced by preferred fracture orientations; therefore, the testing for a non-random fracture pattern is an essential step in most geotechnical investigations of fractured soils. The distribution of fracture set orientations also reveals information pertaining to the fracture-forming processes. Various statistical methods based on random and independent measurements of fractures can be used to determine the probability that a preferred orientation exists.

Most statistical methods for detecting clustering of three-dimensional orientation data involve the use of a Schmidt projection (Hobbs, Means, and Williams, 1976, p. 483-501). When poles are plotted on Schmidt net, the distance between individual observations and the area represented by clusters of observations is not distorted; thus, the data can be contoured to determine if a preferred orientation exists. Contouring is typically done using computer programs based on an algorithm that counts the number of points that lie in an equal area of the plot. The number of points is then converted to a percentage and contour lines are drawn around areas of equal density, allowing fracture sets to be differentiated visually. Orientations for this project were analyzed using a stereonet contouring program called MicroNet (Guth, 1987). This contouring algorithm calculates concentrations of observations per 1% area on a Schmidt net.

If many poles are concentrated in one area of the plot, the fractures represented are interpreted to have a preferred orientation. From an equal-area plot, a three-dimensional version of the Poisson Test, which tests directional data for a non-uniform spherical distribution, called Fisher's distribution (Fisher, 1953), can be used to determine if significant concentrations of points are present (Davis, 1986, p. 341).

To do this, the plot is subdivided into small areas and the observed number of points in each area is tested against the number that represents a statistically significant concentration of points.

The number of points needed to constitute a statistically significant cluster depends on the total number of observations, the dispersion of observations, and the number of significant clusters representing fracture sets. Data sets obtained during this project consist of 55 to 400 observations and two to four clusters of points. For similar data sets analyzed by Connell (1984, p. 74-94.), using the program PATCH (Mahtab and others, 1972), it was determined that clusters containing 5% or more of the total observations in an area equal to 1% of the total area of the plot were usually statistically significant at a 95% level of confidence or above. This concentration was used as a guideline when using contoured diagrams to identify fracture sets.

Because all of the significant clusters detected represented near-vertical fracture sets, it was not necessary to use spherical statistics to determine both the average strike and inclination of the identified fracture sets. Instead, the mean strike direction and dispersion were determined, while an approximate dip direction was estimated visually from the stereonets. Equal-angle rose diagrams, which include only high-angle fractures (> 50°), were also constructed to show orientations of near-vertical fracture sets. These diagrams consist of "petals" that represent 10° class intervals. On this type of rose diagram (equal-angle) the length of each "petal" is proportional to the number of observations in each class.

In theory, the distribution of randomly oriented directional data can be represented by a unit circle (Van Mise frequency distribution) (Davis, 1986, p. 321), and the procedure used for determining the mean azimuth and dispersion involves calculating the resultant vector, which represents the sum of all fracture orientations in the set. This is accomplished by determining the sums and sums of squares of the direction cosines of the observations so that the resultant vector can be resolved. The mathematics used to perform these procedures is discussed in more detail in Davis (1986, p. 316 and chap. 3) and Koch and Link (1971, p. 132).

It is also desirable to be able to identify statistically significant vertical fracture sets (peaks) represented on the rose diagrams. The method used here involves analyzing the frequency of any orientational class independently to determine the significance of a single cluster of observations. Because the samples analyzed here are large, the Poisson distribution is used to approximate the binomial frequency distribution as suggested by Abdel-Rahman and Hay (1978). This method involves identifying peaks by calculating the minimum number of points in one class needed to reject the hypothesis of a random distribution.

The Poisson probability for a specific number of points falling in an observational class (n) is represented by,

$$p(n) = e^{-x}x^{n}/n! \qquad \text{Equation 1}$$

where n is the number of points falling in the observational class of interest, x is the mean number of observations in each class (the total number of observations divided by the number of classes), and e is the natural logarithm base (Abdel-Rahman and Hays, 1978). With this equation, the value of p(n) can be calculated for any size observational class to determine if it has the desired level of significance to represent a peak. This system was applied to some of the data as a guideline to help identify fracture sets.

RESULTS

Bank Erosion Rates

Since 1983, bank erosion rates have been monitored at least two times a year at 20 bank erosion stations established along the shorelines of eastern Lake Sakakawea. From these measurements, seasonal and annual bank erosion rates and the cumulative bank erosion have been determined for each station. Along with determining cumulative bank erosion, variations in seasonal and yearly erosion rates were also identified.

Cumulative bank erosion data for all 20 stations from 1983-1990 (Table 1) show a large variation in erosion rates from station to station. For example, during this period the bank at station 55 in Fort Stevenson State Park has receded nearly 20 metres while at station 50 there has been less than two metres of erosion. These data also show a large variation in bank erosion rates from year to year at a given station; the erosion history for station 1 demonstrates this well (Table 1). Over three metres of bank erosion occurred at this site in 1986, but since then the average bank erosion rate has been less than two centimetres per year.

Frequent measurements made during the first three years reveal that bank erosion is highly variable and tends to be more rapid during the warmer months of May-October, and is especially rapid during summer high lake level conditions when waves erode these banks (Fig. 7) (Appendix I). Conversely, during the colder months, when water levels are typically lower and the banks are usually frozen, very little erosion occurs. Most of the erosion that does take place during the cold season is during March and April when the banks become weakened by cycles of freezing and

TABLE 1

(Yearly/Cumulative Bank Recession cm)

Station	1983/84	84/85	85/86	86/87	87/88	88/89	89/90
1	70/70	290/359	74/433	348/781	3/784	2/786	1/787
2	14/14	208/223	73/296	155/450	2/453	24/477	12/488
3	2/2	347/349	45/394	131/525	-6/518	0/518	11/529
4	12/12	214/226	40/266	362/628	-1/626	3/630	1/630
5	5/5	203/208	5/213	115/328	7/335	-3/332	-15/317
6	45/45	189/234	200/434	339/773	10/783	-5/778	27/805
7	172/172	264/436	133/568	169/737	6/743	157/900	0/900
50	79/79	8/87	22/109	19/128	11/139	19/158	21/178
51	48/48	270/318	24/341	236/578	37/614	7/621	8/629
52	55/55	241/295	13/309	280/589	15/604	-6/598	29/627
53	17/17	62/79	17/96	101/197	12/208	32/240	16/256
54	142/142	373/515	51/565	349/914	3/917	48/966	17/983
55	274/274	545/818	121/939	728/1667	-12/1656	130/1785	75/1859
56	240/240	375/614	100/715	373/1087	127/1214	218/1432	11/1444
57	25/25	127/152	35/186	146/332	23/355	-2/353	-8/346
58	6/6	57/63	43/106	117/224	3/227	52/279	16/294
59	12/12	88/100	44/144	202/346	24/369	6/375	8/367
60	61/61	-4/57	35/92	200/292	-6/286	2/288	-6/282
61	201/201	72/273	52/325	377/702	1/703	16/718	-1/717
62	71/71	88/159	14/174	169/342	56/398	1/399	20/419
Average	76	201	57	246	16	35	12

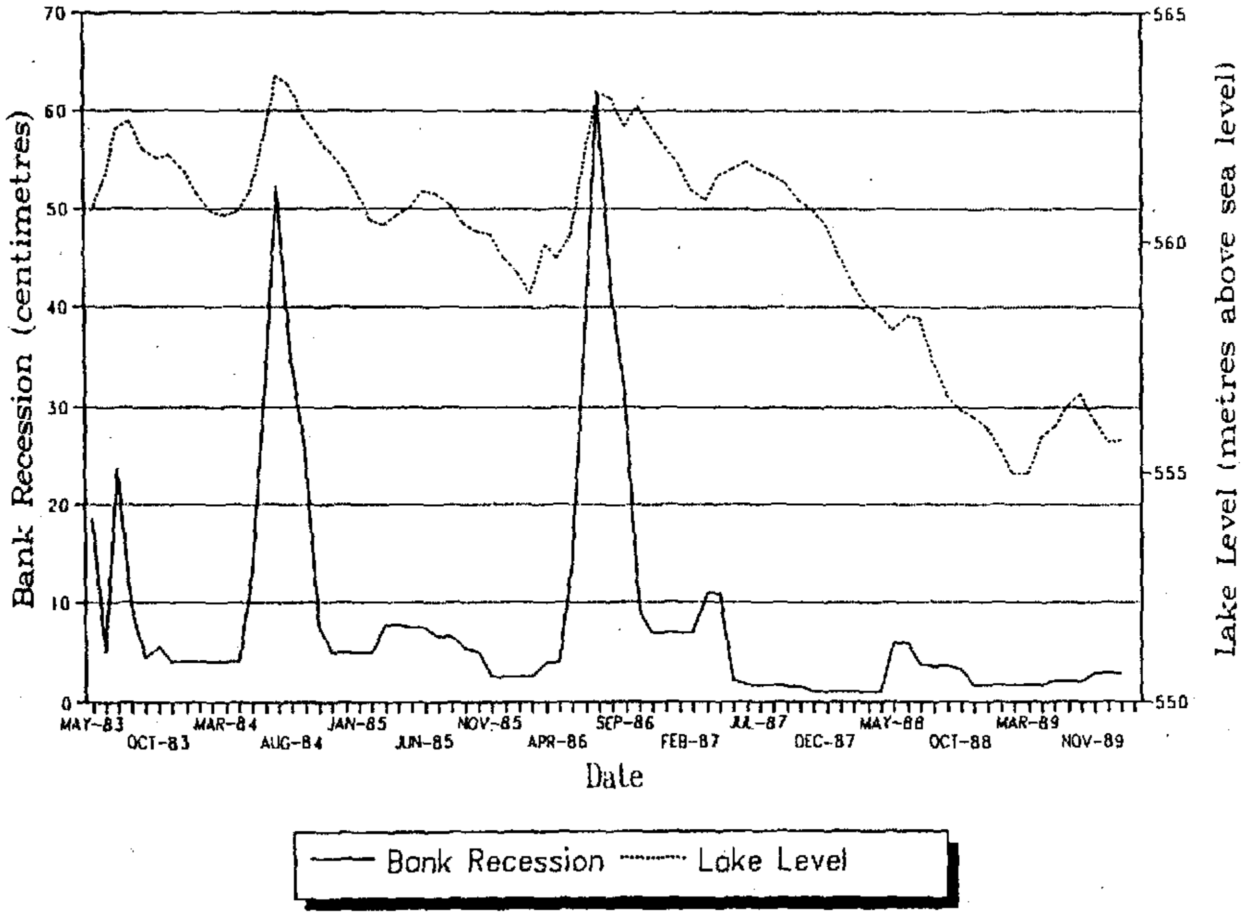


Figure 7. Average Monthly Bank Recession and Lake Levels.

thawing. Thus, for the purposes of monitoring seasonal rates, a warm season (May 1 to October 31) and a cold season (November 1 to April 30) were established (Reid and others, 1988), and bank erosion measurements were taken at least two times a year (at the end of each season) so that seasonal rates could be determined.

The variation in average seasonal rates from station to station is considerable (Table 2). For example, at stations 1 and 59, 100% of the erosion has occurred during the warm season, and at station 60, 75% of the cumulative erosion has occurred during the cold season. However, the majority of bank erosion (77%) takes place during the warm season (Table 2).

Seasonal variations in bank erosion are relatively minor compared to variations associated with lake level fluctuations (Fig. 7). The relationship between high lake levels and increased bank erosion rates (Fig. 7) illustrates that rapid bank erosion is associated with lake levels that equal or exceed 562 metres above sea level for an extended time. This relationship is the basis for defining the "critical lake level" at the 562-metre elevation and above. Even though there has been a total of 72 months of low lake level conditions compared to approximately only 12 months of high lake level conditions since this study began, 56% of the total bank erosion has occurred during the high lake level conditions (Table 3).

Geology

The overall strength of a bank, the mechanisms associated with bank failure and, ultimately, rates of bank erosion are largely controlled by bank geology (Doe, 1980; Edil and Vallejo, 1980). This is particularly true when external processes such as wave action are insignificant. On Lake Sakakawea, wave action is the primary cause of bank erosion; however, because of recent low lake levels, wave action has not been a factor since

TABLE 2

SEASONAL RECESSION RATES
(May 1983 - May 1990)

Station	Total		Average		Percent	
	Warm (cm)	Cold (cm)	Warm (cm/mo)	Cold (cm/mo)	Warm %	Cold %
1	792	-1	19	0	100	0
2	370	119	9	3	76	24
3	511	24	12	1	95	5
4	583	49	14	1	92	8
5	287	30	7	1	91	9
6	577	228	14	5	72	28
7	594	307	14	7	66	34
50	104	74	2	2	59	41
51	551	77	13	2	88	12
52	573	54	14	1	91	9
53	140	116	3	3	55	45
54	853	130	20	3	87	13
55	1182	689	28	16	63	37
56	975	469	23	11	67	33
57	188	157	4	4	54	46
58	254	41	6	1	86	14
59	373	-5	9	0	100	0
60	72	216	2	5	25	75
61	590	128	14	3	82	18
62	337	82	8	2	80	20
Average	485	141	12	4	77	23

TABLE 3

HIGH AND LOW LAKE RECESSION RATES
(May 1983 - October 1989)

Station	Total		Rate		Percent	
	High (cm)	Low (cm)	High (cm/mo)	Low (cm/mo)	High %	Low %
1	641	150	53	2	81	19
2	275	214	23	3	56	44
3	451	84	38	1	84	16
4	568	64	47	1	90	10
5	283	34	24	0	89	11
6	405	400	34	6	50	50
7	243	657	20	9	27	73
50	32	146	3	2	18	82
51	465	163	39	2	74	26
52	498	129	42	2	79	21
53	84	172	7	2	33	67
54	789	293	57	4	70	30
55	817	1055	68	15	44	56
56	489	955	41	13	34	66
57	158	188	13	3	46	54
58	169	126	14	2	57	43
59	284	83	24	1	77	23
60	-7	295	-1	4	0	100
61	449	269	37	4	63	37
62	219	200	18	3	52	48
Average	361	284	30	4	56	44

the fall of 1986. Despite these recent low lake level conditions, bank recession has continued, but at much slower rate (Fig. 7); thus, identifying those geological factors influencing recession rates during low lake level periods and assessing their importance is appropriate.

Bank geology consists of all internal characteristics of shoreline banks, including the bank geometry (height, slope, and orientation), the composition of the bank material, and physical properties of the material, such as grain size, strength, and drainage characteristics. The current study, involves describing and assessing the affects of structural features such as fractures, bedding, and concretions which are also important components of bank geology. Other factors and processes related to wave and frost action and bank and beach geometry were assessed during earlier phases of this project (Reid and others, 1988).

Sentinel Butte Formation

General

The Sentinel Butte Formation (Paleocene), is the oldest geologic unit exposed along the shoreline of eastern Lake Sakakawea, (Fig. 3). The Sentinel Butte Formation is not lithologically homogeneous; it is a repetitive sequence consisting primarily of grey and light-brown to tan poorly-consolidated mudstone, sandstone, lignite, and concretionary limestone lenses. Bedding is well-developed at most of the locations, and in the study area beds are all nearly horizontal and typically 10 to 25 cm thick. They are defined mostly by slight changes in color and texture; however, this unit also contains many highly-fractured lignite layers, relatively well-indurated limestone lenses, massive clay-rich layers, and large channel-shape deposits of poorly consolidated, cross-bedded, and poorly sorted silty sand. Other structures in the mudstone include large spherical limonitic and calcareous concretions which may be up to two metres in diameter, and pieces of white petrified wood that are concentrated in lignite layers. The Sentinel Butte Formation is described in greater detail by Crawford (1967) and Jacob (1976).

For the purposes of discussing various types of fracture patterns, the Sentinel Butte Formation exposures included in this study have been separated into three informal subunits: mudstone, sandstone, and lignite. Fracture lengths and densities are considerably different in each of these subunits.

The most abundant Sentinel Butte lithology in this study area is a poorly consolidated bedded silty clay (mudstone). This is the dominant lithology at seven of the 20 bank erosion stations. Bedding in this material is defined by slight color changes and by weakly-developed horizontal fractures which have developed along bedding contacts. Textural analyses (Millsop, 1985, p. 54) revealed average sand-silt-clay percentages of 2, 47, and 50 %, respectively. Additional textural and physical data are also reported by Millsop (1985, Appendix A). X-ray diffraction analyses (Millsop, 1985) indicate that smectite is the dominant clay mineral in the clay-size fraction of the mudstone.

Channel sandstone deposits were studied at two sites, near station 57, in Fort Stevenson State Park, and near the Government Bay launch facility, approximately one mile northeast of Riverdale. These are large channel-shape deposits of poorly-consolidated light-grey, thinly cross-bedded silty sands. Thin small-scale cross beds are ubiquitous upon close inspection; however, these deposits appear massive and homogeneous from a distance. Because it is the dominant lithology only at station 57, this subunit is relatively unimportant with regard to this study, but is important at other locations around the lake.

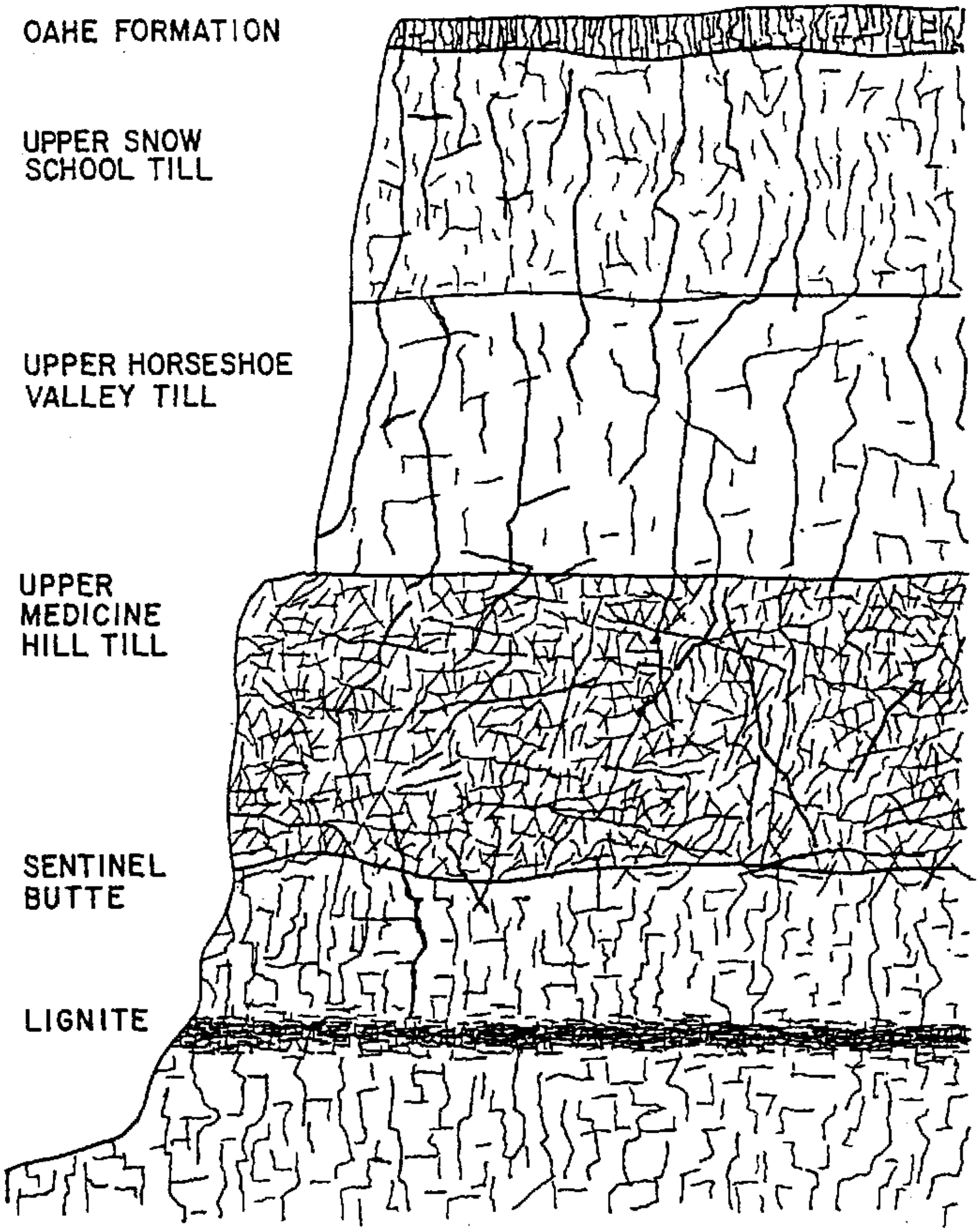
Highly fractured lignite layers, usually less than a metre thick, are interbedded with Sentinel Butte mudstone at many exposures. The lignite is a brittle and moderately consolidated low-grade coal which contains scattered silicified pieces of white petrified wood. Lignite is not a dominant lithology at any of the bank erosion stations; the layers may be significant, however, in that they appear to be associated with greatly increased fracture densities in the adjacent mudstone, and because they are a horizontal discontinuity.

Fractures

General: Due to the presence of relatively evenly spaced intersecting horizontal and vertical fractures, the Sentinel Butte mudstone typically has a blocky appearance (Fig. 8 and 9). The blocky pattern is not as apparent where bedding and horizontal fracturing is absent or very weakly developed; however, well-developed vertical fractures still persist at all locations. The frequency of both horizontal and vertical fractures increases greatly near and in lignite layers and tends to decrease in zones containing more sand. Horizontal fracture parallel and appear to be controlled by the frequency of bedding contacts in this unit (Fig. 8 and 9).

Horizontal Frequencies: The results for seven Sentinel Butte Formation sites (Table 4) are typical of horizontal fracture frequencies observed at other sites where the trend of fewer fractures in sandy lithologies and greater fracture densities in and near lignite layers is also observed.

Vertical Frequencies: Sets of near-vertical (vertical) fractures are well developed in the Sentinel Butte Formation at all of the observed sites. As with the horizontal frequencies, the vertical fracture frequencies are low for the sandstone exposures (1.9/m and 1.6/m) and high for the lignite exposure (Table 5); the frequencies (4.2-5.0/m) for the mudstone exposures are rather similar. Again, these fracture frequencies appear to be typical of most other Sentinel Butte exposures in this area.



<u>Figure 8</u>. Characteristic Fracture Patterns for the Dominant Bank Lithologies.

Figure 9. Blocky Fracture Pattern and Variable Lithologies, Sentinel Butte Formation.

TABLE 4

HORIZONTAL FRACTURE FREQUENCIES

Location/Unit	Number of Fractures	Frequency
Sentinel Butte Sandstone		
Station 50	46	3.1/m
Station 57	38	1.8/m
TOTAL	84	2.3/m
Sentinel Butte Mudstone		
Station 2	44	8.8/m
Station 53	18	4.5/m
Stations 54 and 55	46	4.2/m
TOTAL	108	5.4/m
Sentinel Butte Lignite		
Station 50	46	23.0/m
Stations 60, 61, and 62	55	15.7/m
TOTAL	101	17.6/m
Upper Medicine Hill Till		
Station 51	97	8.8/m
Station 53	50	4.5/m
Station 58	50	6.0/m
Station 59	46	3.6/m
TOTAL	243	5.7/m
Upper Horseshoe Valley Till		
Station 51	19	0.8/m
Station 52	22	0.9/m
Stations 60, 61, and 62	11	0.9/m
TOTAL	52	0.8/m
Upper Snow School Till		
Lake Sakakawea State Park	54	1.2/m
Stations 6 and 7	38	2.5/m
TOTAL	92	1.4/m
Oahe Formation		
Lake Sakakawea State Park	45	2.9/m

TABLE 5

HIGH-ANGLE FRACTURE FREQUENCY

Location/Unit	Number of Fractures	Frequency
Sentinel Butte Sandstone		
Station 50	29	1.9/m
Station 57	8	1.6/m
Total	37	1.9/m
Sentinel Butte Mudstone		
Station 2	50	4.2/m
Station 53	28	4.7/m
Stations 54 and 55	80	4.4/m
Station 56	61	5.0/m
Total	219	4.5/m
Sentinel Butte Lignite		
Station 50	46	23/m
Upper Medicine Hill Till		
Station 51	48	5.3/m
Station 53	19	2.5/m
Stations 58 and 59	154	6.7/m
Total	221	5.6/m
Upper Horseshoe Valley Till		
Station 51	30	2.0/m
Station 52	58	2.7/m
Total	88	2.4/m
Upper Snow School Till		
Station 1	48	3.2/m
Station 3	62	3.1/m
Station 4	95	4.5/m
Station 5	71	4.2/m
Stations 6 and 7	73	2.4/m
Stations 60, 61, and 62	23	2.6/m
Total	372	3.3/m
Oahe Formation		
Station 1	120	8.0/m
Station 3	50	10/m
Station 4	73	10/m
Total	243	9.0/m

Vertical Lengths: The average vertical fracture lengths for the four mudstone sites (16, 39, 58, and 63 cm) (Table 6) vary considerably, suggesting that the average length of such fractures is controlled by factors that are not consistent among different exposures of this unit; thus, estimates of vertical fracture lengths for this unit at a given location should not be based on data from other sites. The high standard deviations are a reflection of the large variation in vertical fracture lengths. Individual fractures range from about 5 to 500 cm long, but the majority are 20 to 60 cm long (Appendix VII).

The average vertical fracture lengths in the three sandstone exposures (64, 229, and 39 cm) vary even more than the mudstone averages. The dominance of large vertical fractures in the massive thinly cross-bedded silty channel sands near the Government Bay launch facility has not been observed elsewhere in this area. Still, even excluding this site, vertical fractures tend to be longer in sandstone lithology. The lower than average lengths at station 57 are not representative of lengths in most channel sand outcrops. Smaller lengths here are the result of relatively strong interbedded lenses of concretionary limestone at this site. Vertical fracture lengths were not measured in any of the lignite layers; however, they tend to be small and closely spaced in this unit (Fig. 8).

Orientations: Orientations of over 500 Sentinel Butte fractures were measured at four different areas along the shorelines of eastern Lake Sakakawea. As discussed earlier, only the orientations of nonhorizontal fractures (fractures dipping at an angle greater than 10° from horizontal) were measured and included in these data sets. The results of these measurements are represented both as points, which are poles to fracture planes (Fig. 10a), and as density contours of these points (Fig. 10b).

TABLE 6

HIGH-ANGLE FRACTURE LENGTHS

Location/Unit	Number of Fractures	Mean Length (centimetres)	Standard Deviation
Sentinel Butte Sandstone			
Lake Sakakawea State Park	15	64	59
Gov. Bay Launch Facility	46	229	120
Fort Stevenson State Park	62	39	29
Total	123	101	83
Sentinel Butte Mudstone			
Lake Sakakawea State Park	81	39	50
Station 50	18	63	57
Fort Stevenson State Park	121	58	36
Stations 60, 61, and 62	50	16	12
Total	270	43	41
Upper Medicine Hill Till			
Station 51	88	34	36
Station 53	95	32	29
Stations 58 and 59	114	30	48
Total	297	32	39
Upper Horseshoe Valley Till			
Station 51	57	68	52
Station 52	39	118	45
Station 60	54	72	37
Total	150	81	46
Upper Snow School Till			
Lake Sakakawea State Park	129	39	26
Stations 6 and 7	82	38	38
Total	212	39	32

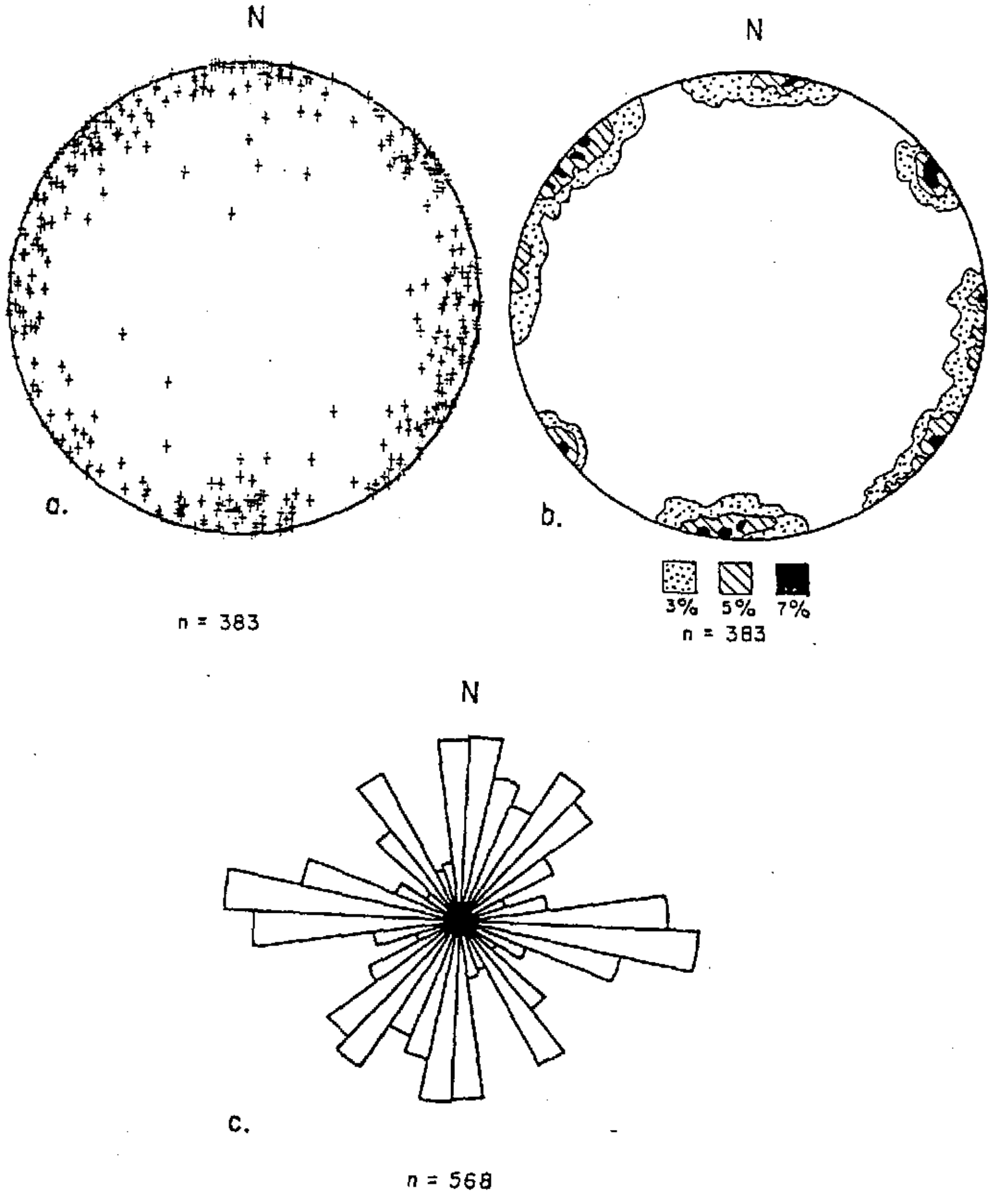


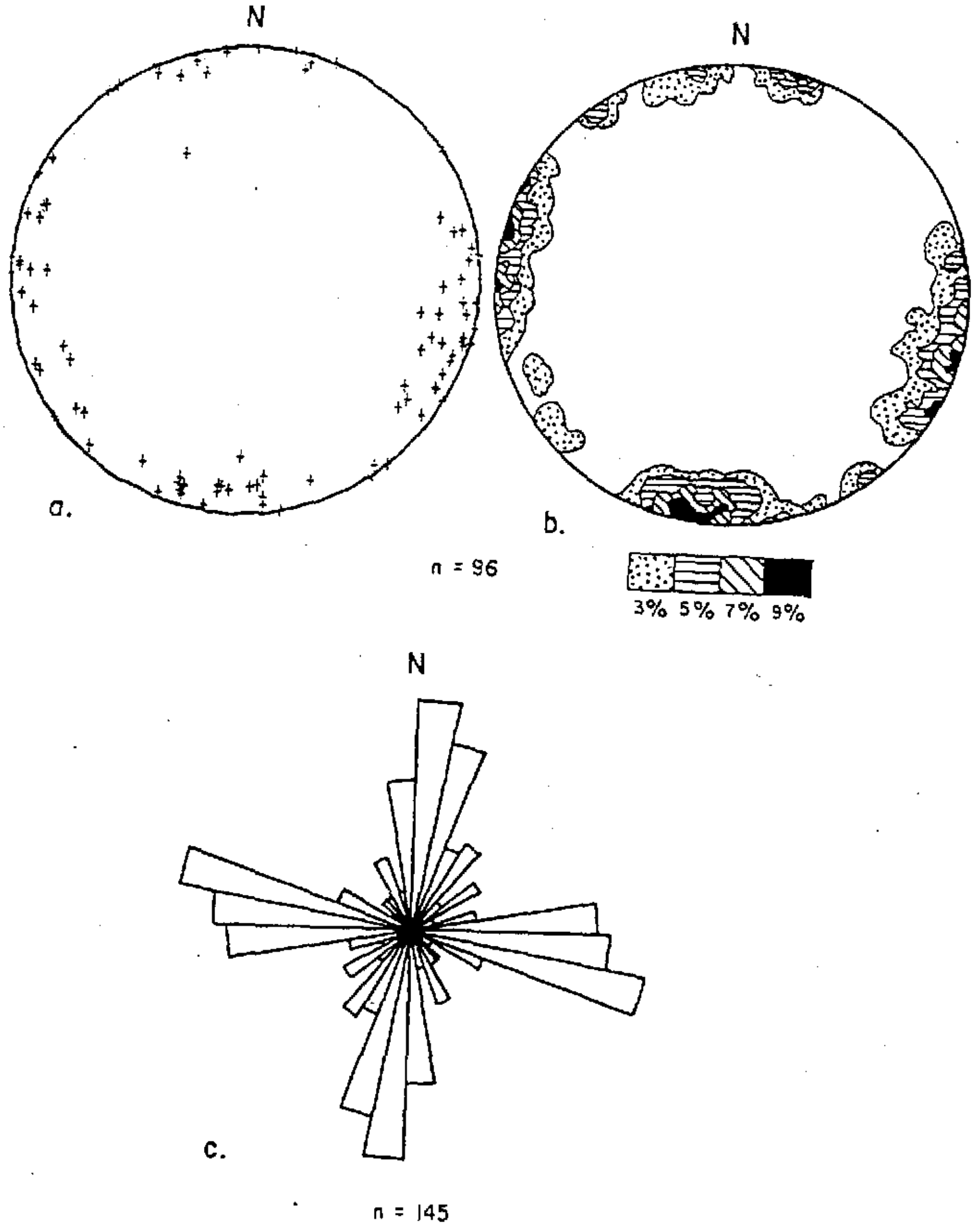
Figure 10. Sentinel Butte Formation Fracture Orientations, Eastern Lake Sakakawea, (a = lower hemisphere equal-area stereonet projection of poles to fracture planes, b = resulting contours of the percent total number of points for each one percent area, c = equal-angle rose diagram showing the azimuths of high-angle (>50° dip) fractures).

These data indicate an absence of persistent sets of obliquely oriented fracture sets in the Sentinel Butte Formation. Therefore, only the average strike direction was determined for each fracture set, and the dips are reported as near-vertical (vertical). This same procedure was used to identify fracture set orientations in the other till units which contain mainly high-angle fractures as well. Part c of these diagrams include only high-angle fractures with dips of > 50° and may include additional strike directions of fracture surface traces exposed on the wave-eroded beach surfaces, thus, explaining the difference in number of observations listed for the rose diagrams.

At Lake Sakakawea State Park there are two dominant sets of vertical fractures, one striking roughly E-W with an approximate orientation of 93°, and one roughly N-S, with an approximate orientation of 10° (Fig. 11). Most of the remaining fractures are also vertical and there is one less well-defined set at approximately 149°.

The majority of fractures measured near the Government Bay launch facility and station 50 are NE-SW trending and are vertical (Fig. 12). The average strike of this set is approximately 30°. The resulting diagrams also show the presence of three other relatively weakly developed vertical fracture sets trending approximately N-S, E-W, and NW-SE at about 173°, 86°, and 136°, respectively.

At Fort Stevenson State Park (Stations 53, 54, 55, 56, and 57) most of the fractures are vertical or nearly vertical. There are four major fracture sets oriented roughly N-S, E-W, NW-SE, and NE-SW with average azimuths of 6°, 91°, 48°, and 139° (Fig. 13). The NE-SW, N-S, and E-W sets, consist mostly of vertical fractures and fractures dipping steeply to the SE. The NW-SE trending set consists mostly of fractures dipping steeply to the SW.



<u>Figure 11</u>. Sentinel Butte Formation Fracture Orientations, Lake Sakakawea State Park.

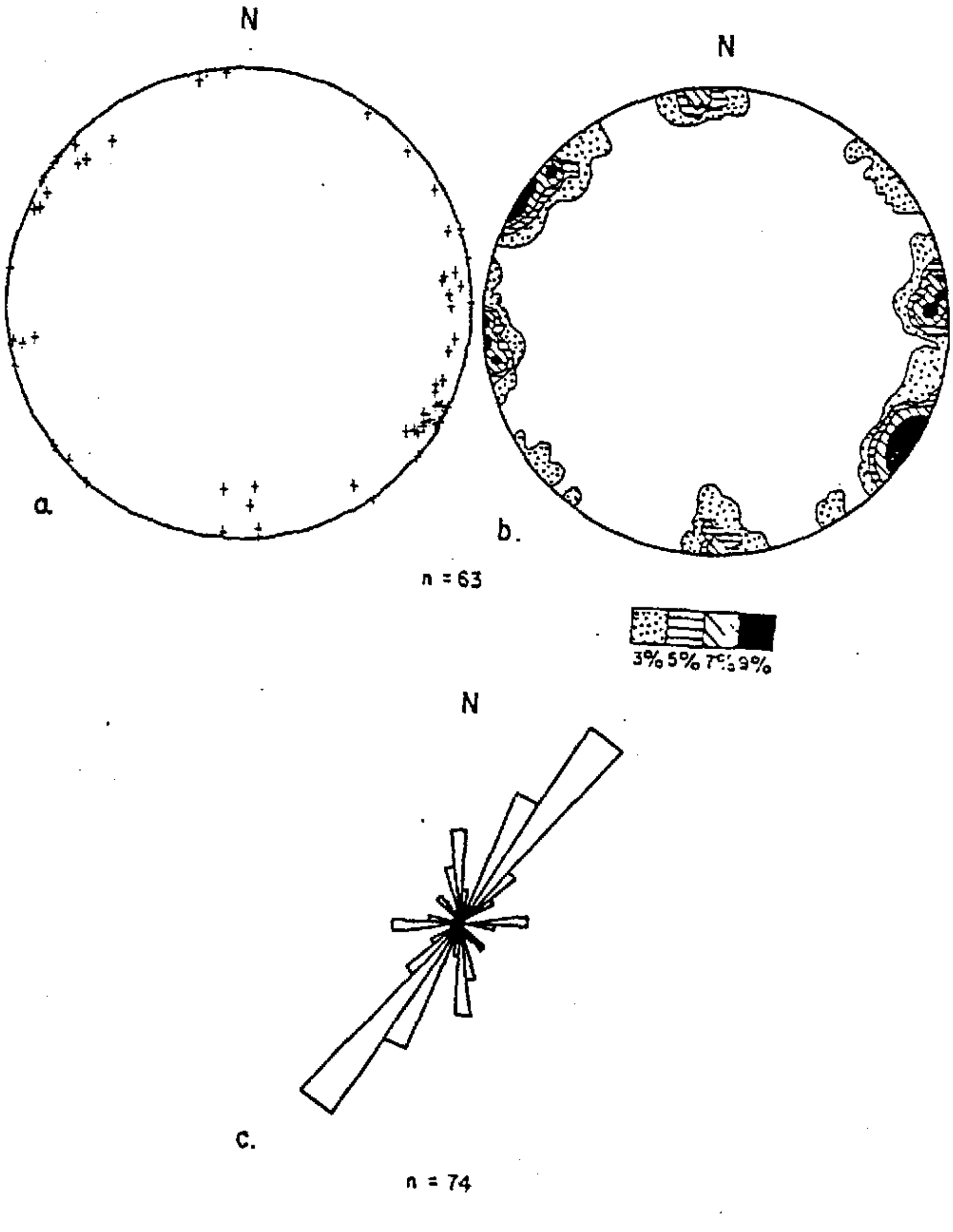


Figure 12. Sentinel Butte Formation Fracture Orientations, Station 50 and Government Bay Launch Facility.

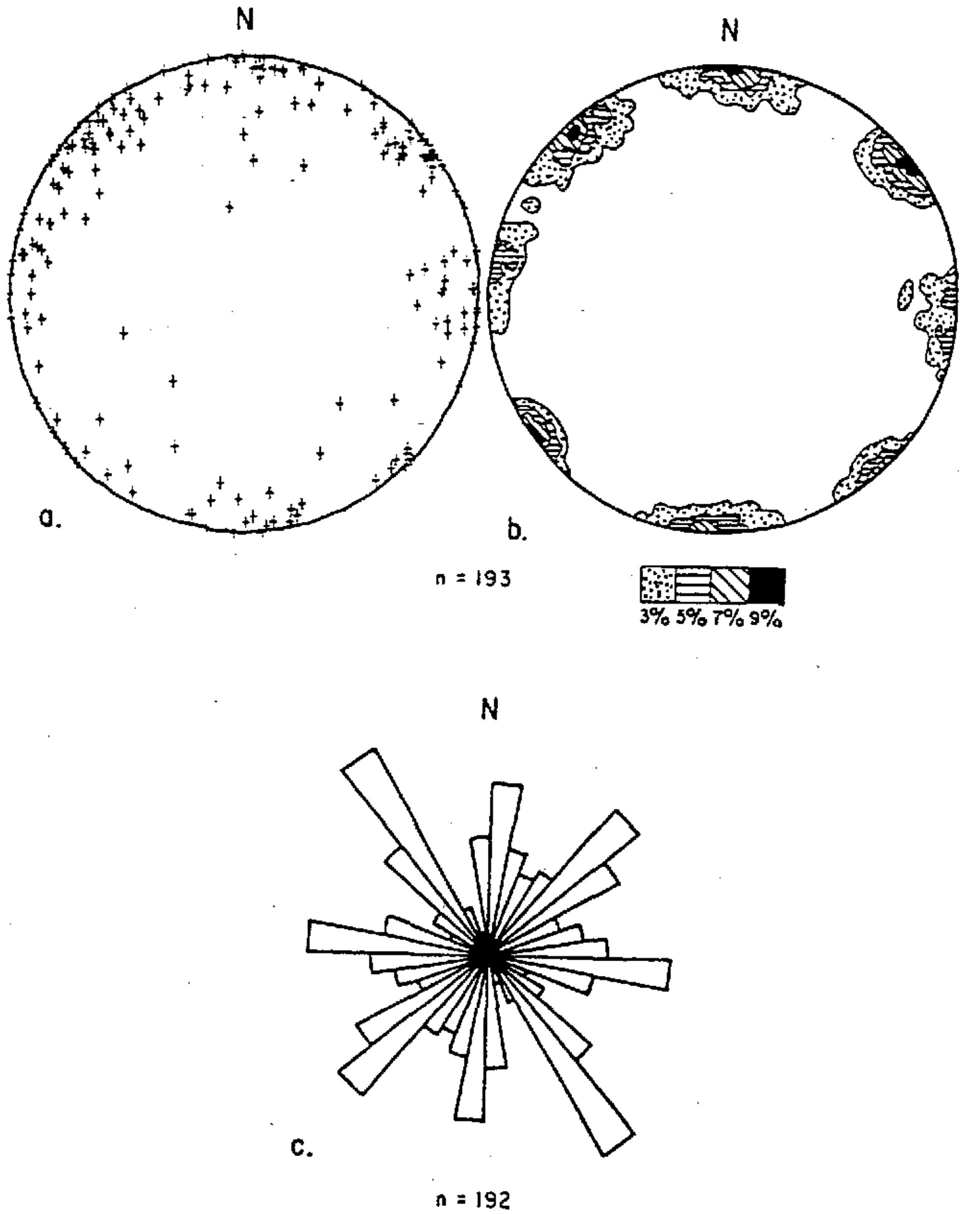


Figure 13. Sentinel Butte Formation Fracture Orientations, Fort Stevenson State Park.

Even though four separate fracture sets are easily distinguishable from these data, the overall distribution is essentially random when assessing its affect on the directional variations in strength of banks in this area. Because there are four fracture sets oriented approximately 45° from each other, the orientation of any bank face will be nearly subparallel to at least one of the fracture sets.

Most of the Sentinel Butte Formation fractures near stations 60-62 area also horizontal or nearly vertical (Fig. 14). In this vicinity, there are also four main sets of vertical fractures which have approximate orientations of 3°, 92°, 42°, and 140°. Again, the effect is to weaken bank resistance to failure nearly equally for all bank directions.

There is, therefore, a similar pattern of fracture orientations at each of the Sentinel Butte sites studied. Nearly all of the nonhorizontal fractures have vertical or near-vertical orientations, and four sets of vertical fractures oriented approximately N-S, E-W, NE-SW, and NW-SE are consistently represented in this area. Even though some sets are more strongly developed at particular sites (e.g., the NW-SE set at the Government Bay launch facility and the N-S and E-W sets at Lake Sakakawea State Park), orientations from each of these four sets are represented at each of the sites.

Other: In addition to measuring fracture lengths and orientations, the geometry and surface characteristics were also recorded. (Appendix III). Most horizontal and vertical fractures observed in the Sentinel Butte Formation are straight, as opposed to having a curved or irregular geometry, and most have matte surfaces, and very few surfaces are smooth,irregular, or rough. Also, the presence of mineral coatings was seldom observed, and no surface markings such as plumose structures, slickensides, or pits were seen on any of the Sentinel Butte fractures.

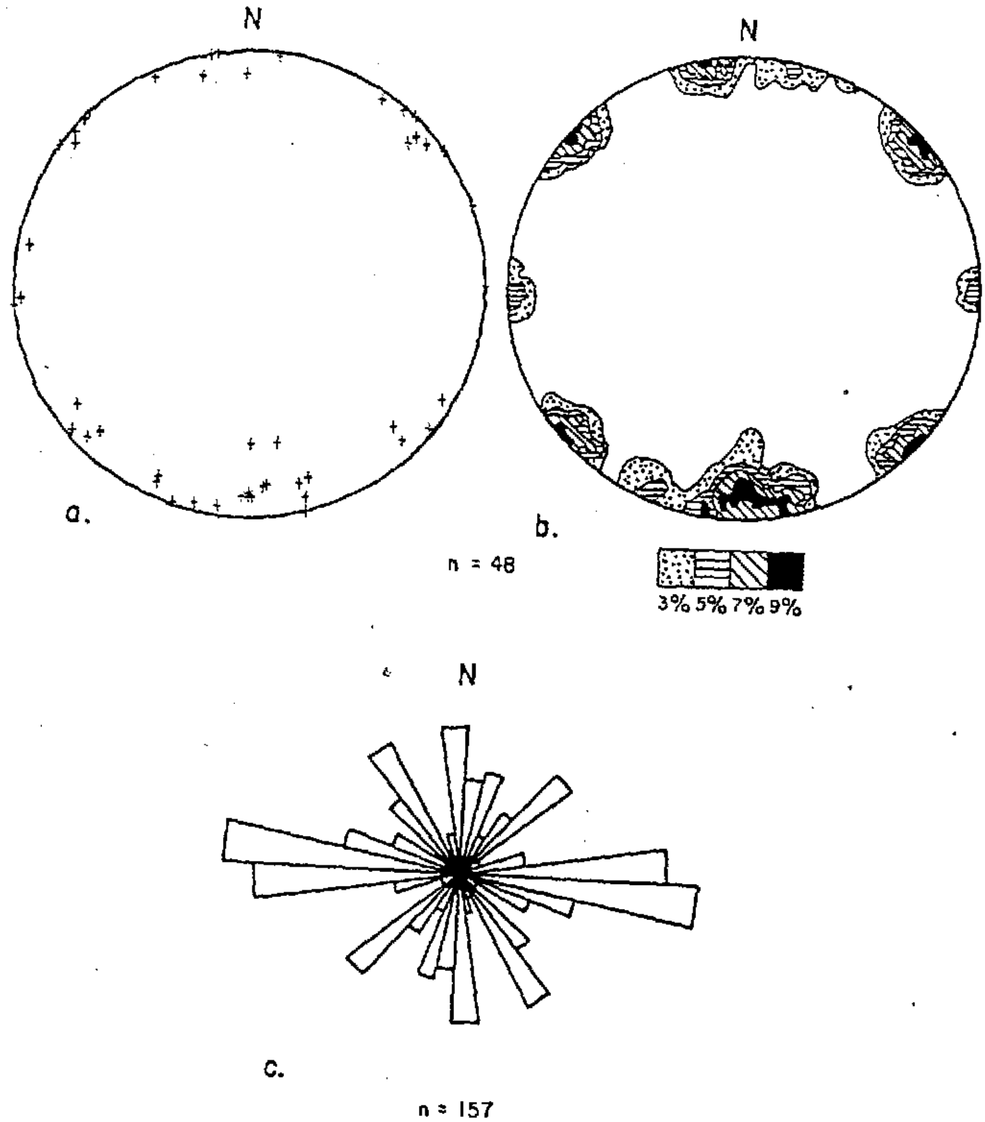


Figure 14. Sentinel Butte Formation Fracture Orientations, Stations 60, 61, and 62.

Upper Medicine Hill Till

General

The Medicine Hill Formation, which is part of the Pleistocene Coleharbor Group (Ulmer and Sackreiter, 1973), consists of two distinct members. The lower member is unconsolidated sand, pebbles, and cobbles that is locally cemented (Ulmer and Sackreiter, 1973). This member is not exposed at any of the bank recession stations or other locations studied during this project. Exposures of the upper member, however, are up to 15 m thick along the shoreline bluffs of eastern Lake Sakakawea. This member is the dominant lithology at stations 53, 58, and 59, and is also exposed at station 51.

The upper member, interpreted to be a till (Millsop, 1985, p. 54), is a light brownish-grey to light grey dense pebble loam. The average sand-silt-clay fractions are about 25, 45, and 30%, respectively, (Millsop, 1985; Ulmer and Sackreiter, 1973). This till unit also contains scattered pebbles, cobbles, and boulders which form lag deposits on the beaches as bank erosion proceeds and the finer material is carried away (Fig. 15). The samples tested by Millsop (1985, p.55) had higher dry densities than the other till units in this area. The Upper Medicine Hill till also contains large inclusions of thinly-bedded and cross-bedded sandy silt. Several of these silt inclusions are incorporated into the till exposure at station 58 (Fig. 16).

Fractures

General: From a distance, silt inclusions and scattered boulders can be seen in the Upper Medicine Hill till, but otherwise it appears to be homogeneous. Upon closer examination, from a few metres away, however, this till appears highly fractured. From a casual observation the fracture patterns appear to be random or complex (Fig. 8). There are many slightly curved low-angle and nearly-horizontal fractures which are

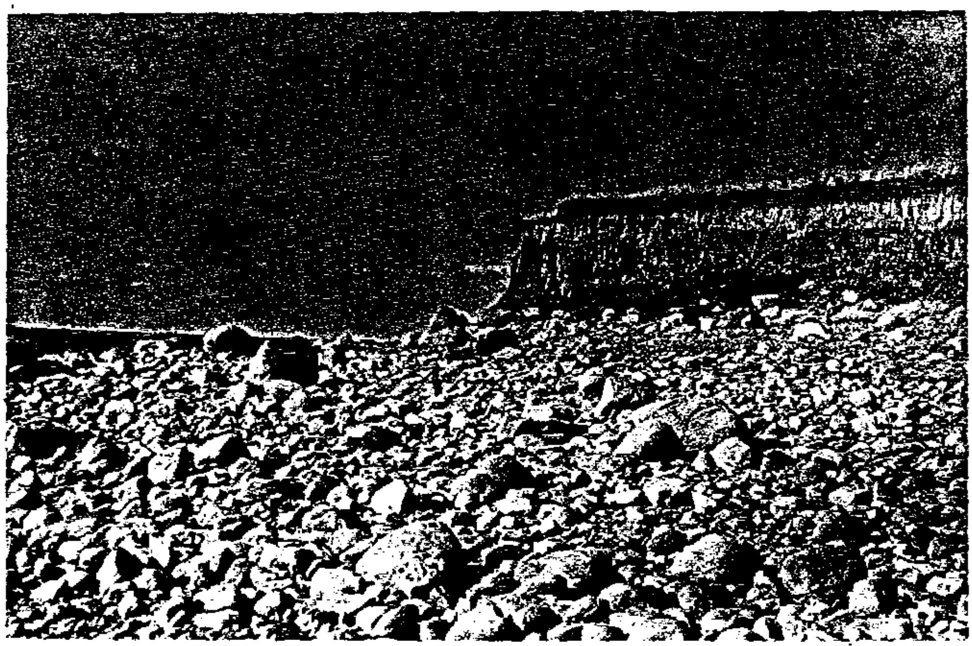


Figure 15. Boulder Beach near Station 51.

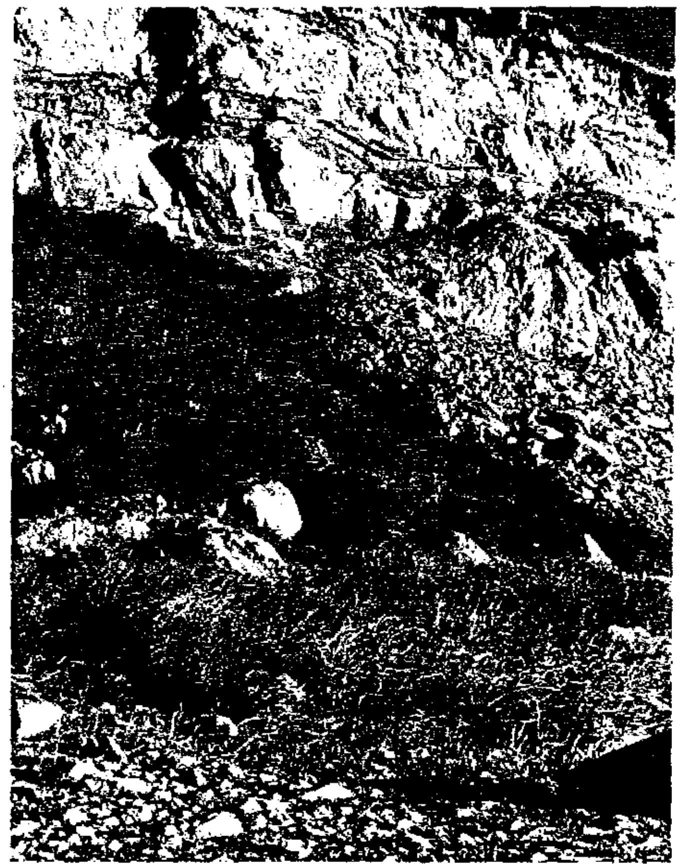


Figure 16. Upper Medicine Hill Till with Silt Inclusions, Station 58.

intersected or cut by seemingly randomly oriented oblique and steeply dipping straight and irregular fractures of various lengths. In many cases, series of near-vertical short subparallel fractures can be seen between longer low-angle slightly curved fractures (Fig. 17).

Nearly all of the fractures in this till unit are filled or coated with deposits of carbonates and gypsum, and many of the fracture surfaces and mineral deposits in the fractures are stained with red or yellowish-orange iron oxides. The majority of the fractures in this dense till are closed or have been sealed by mineral coatings. Because nearly all of the fractures are sealed or are coated or stained with mineral material, it usually was not possible to examine fracture surfaces for textures or markings.

Horizontal Frequencies: The horizontal fracture frequencies in the Upper Medicine Hill till at stations 51, 53, 58, and 59 varied considerably. They ranged from 3.6/m at station 59 to 8.8/m at station 51 (Table 4). This is similar to the variations obtained for the Sentinel Butte mudstone, and again, slight compositional variations from site to site might be causing these variations, or they might be accounted for by the presence of associated structures such as silt or gravel lenses or large boulders. Even though these data show a considerable degree of variation in horizontal fracture frequencies from site to site, they do clearly indicate that the average horizontal fracture density in this till is consistently higher than in the Upper Snow School and the Upper Horseshoe Valley tills (Table 4).

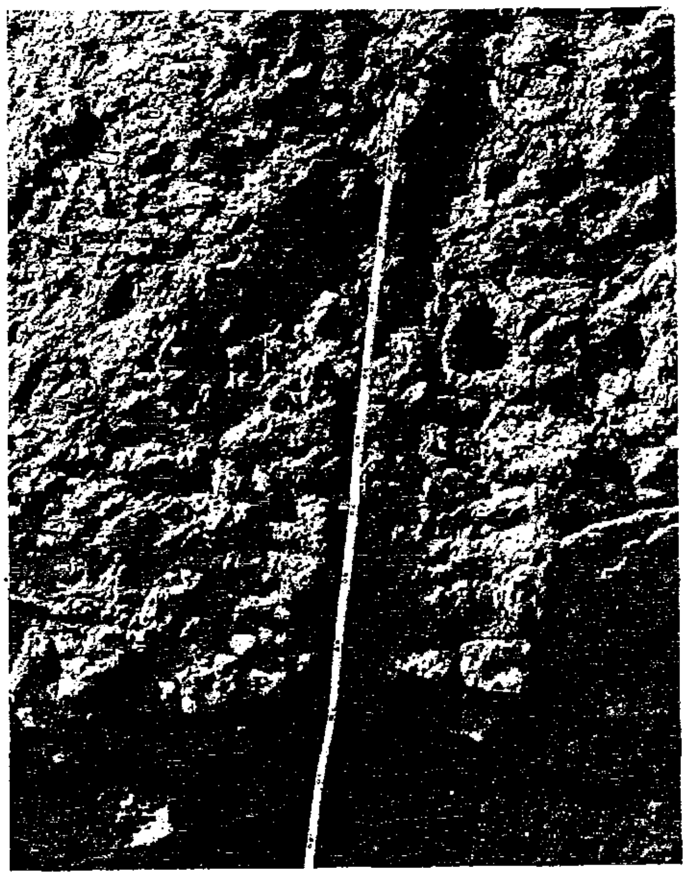


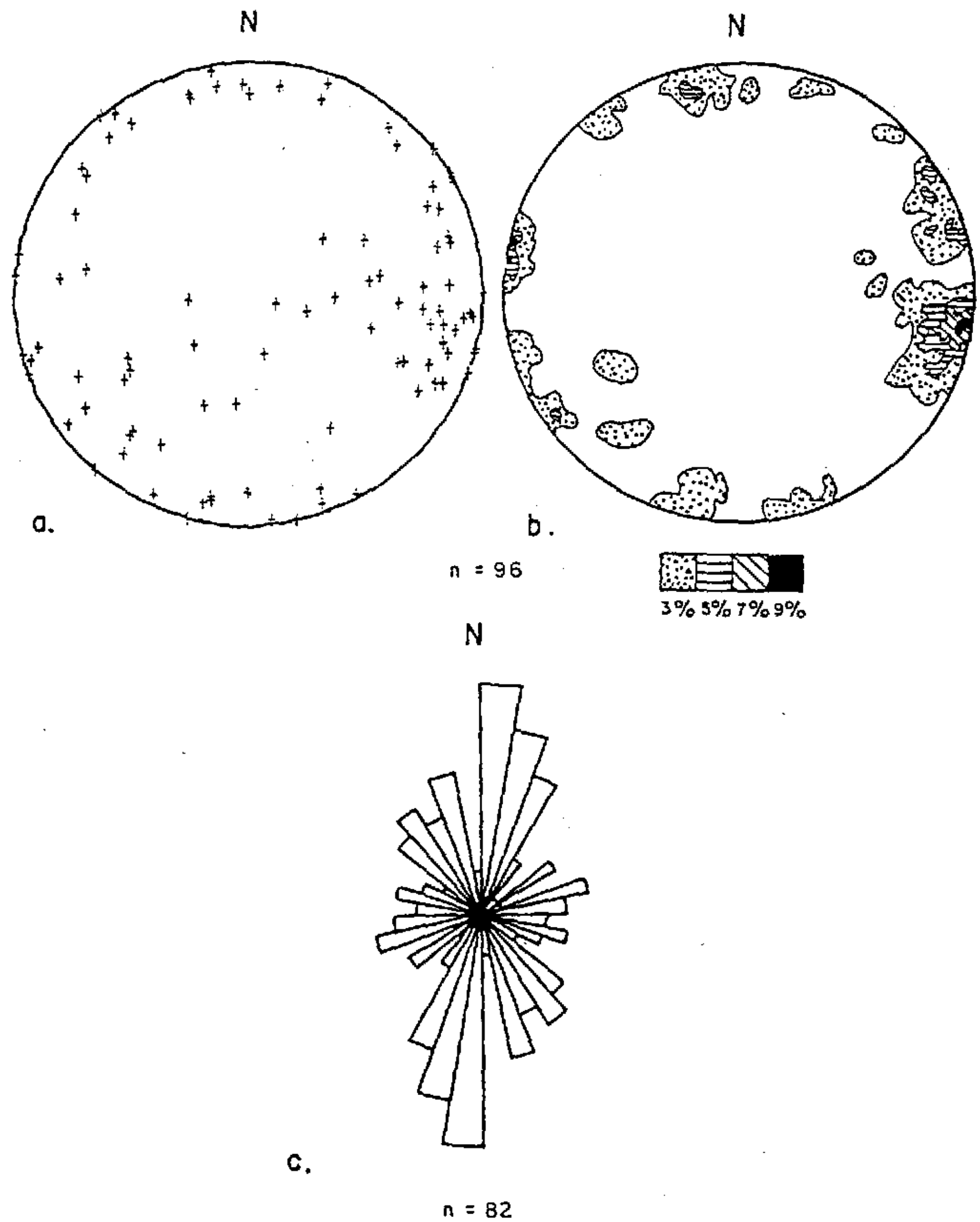
Figure 17. Close-Up of Upper Medicine Hill Till Fractures, Station 51.

__Vertical Frequencies:__ Vertical fracture frequencies were measured in the Upper Medicine Hill till at stations 51, 53, 58, and 59. Again, there is a rather large variation of frequencies (Table 5) which may be due to lithologic variations and the presence of structures, especially horizontal fractures.

__Lengths:__ The average vertical fracture lengths in the Upper Medicine Hill till at stations 51, 53, 58, and 59 are all relatively low; they ranged from 30 to 34 cm (Table 6). Variations in average fracture lengths from site to site in this unit are small. Nevertheless, as is the case for each of the other units, the standard deviations for these data sets are high, indicating a wide range of fracture lengths at a given location. Most of the fractures in this unit are between 20 and 60 cm long, but range from less than 5 to over 400 cm; however, when compared to some of the other lithologies, there are relatively few fractures over 100 cm in length (Appendix III).

__Orientations:__ The dispersion of fracture orientations in the Upper Medicine Hill till at station 51 is high (Fig. 18). Whereas most of the fractures at this site are oriented vertically or nearly vertical, many are also dipping at low or oblique angles. There is only one well-defined high-angle fracture set, oriented N-NE to S-SW at approximately 14° (Fig. 18). Most of the fractures in this set are dipping steeply to the NW at 55°-80°. The rose diagram and the stereonet plot (Fig. 18a,c) suggests the possibility of two more weakly developed sets, one with fractures striking at about 75° and the other striking at approximately 148°; however, these sets have a low statistical significance.

At station 53, 96 fracture orientations were measured in the Upper Medicine Hill till. These are mostly high-angle fractures, distributed in tighter clusters than at station 51, except for a relatively weakly



<u>Figure 18</u>. Upper Medicine Hill Till Fracture Orientations, Station 51.

defined cluster dipping at a low angle to the W and SW (Fig. 19). Also, these diagrams show the presence of two vertical sets, both consisting of high-angle fractures and with a high degree of directional dispersion. The N-NW to S-SE set has an approximate average orientation of 161° and the E-W set has an approximate orientation of 87°.

At stations 58 and 59, again, there is a high degree of directional dispersion for this till (Fig. 20). The Upper Medicine Hill till in this area contains mostly vertical and near-vertical fractures and also hosts a large number of fractures dipping at oblique angles (Fig. 20). There are also two distinct steeply dipping fracture sets, one oriented nearly E-W at approximately 85°, and the other NE-SW at approximately 47°. A third more poorly defined NW-SE trending set of high-angle and oblique fractures, dipping to the SW and NE, is also apparent on these diagrams. However, the statistical significance of this set is low (Fig. 20b).

The distributions of fracture orientations at these three Upper Medicine Hill till sites (Fig. 18-20) are dissimilar. The interpretive diagrams do indicate a high degree of dispersion of fracture orientations. Although near-vertical and vertical fractures are dominant at each site, there are many fractures dipping at oblique and low angles, too. Each site has at least one significant set of steeply dipping fractures; the orientations of these sets vary between sites, however.

Upper Horseshoe Valley Formation

General

The Horseshoe Valley Formation (Ulmer and Sackreiter, 1973), which is the middle formation in the Pleistocene Coleharbor Group, is stratigraphically above the Medicine Hill Formation and below the Snow School Formation (Fig. 3). This formation also has an upper and a lower member. The lower member is a discontinuous bedded iron-stained conglomerate overlain by a poorly sorted, medium-grained, cross-bedded,

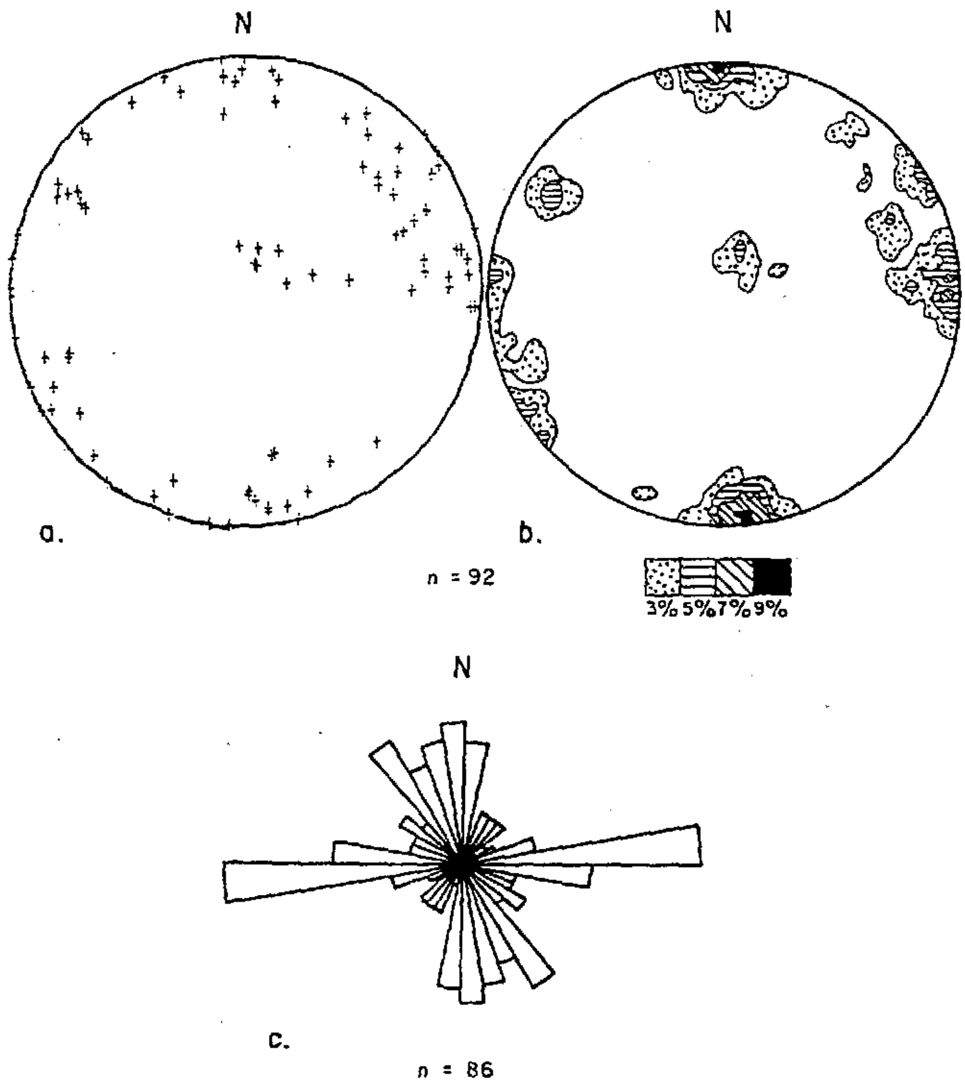


Figure 19. Upper Medicine Hill Till Fracture Orientations, Station 53.

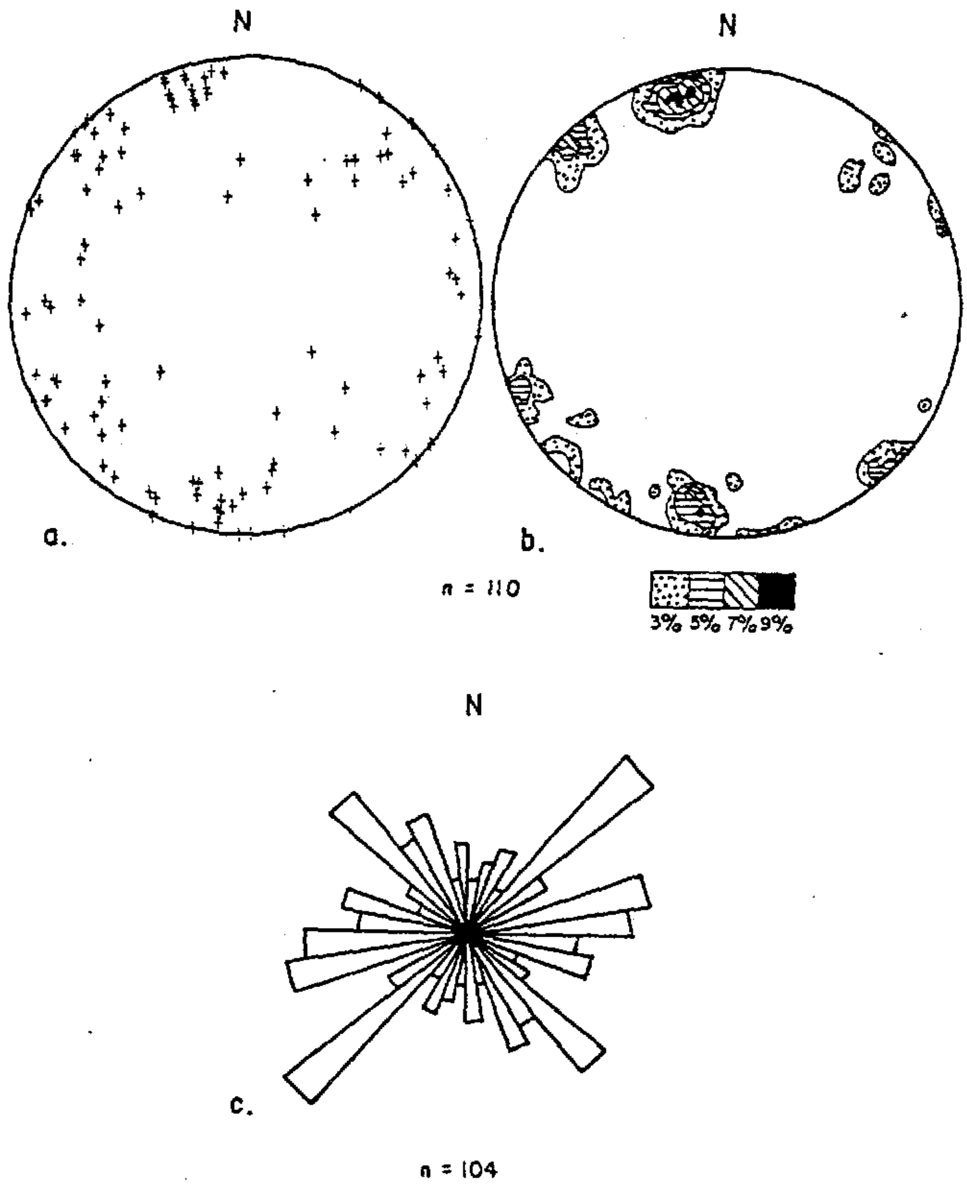


Figure 20. Upper Medicine Hill Till Fracture Orientations, Stations 58 and 59.

light-yellowish-brown sand (Millsop, 1985, p.60). Where present, the lower member averages less than a metre thick (Ulmer and Sackreiter, 1973), and the thin layer at Station 51 represents the only occurrence of this geologic unit at the bank recession stations.

The Upper Horseshoe Valley till is a light brownish-grey to light-yellowish-brown poorly sorted pebble loam, interpreted as a till (Millsop, 1985, p.61). This till is less dense than the Upper Medicine Hill till and consists of roughly equal amounts of sand, silt, and clay (Millsop, 1985, p.61 and Ulmer and Sackreiter, 1973). It also contains widely scattered small sand and gravel lenses and scattered boulders, cobbles, and pebbles.

Where it is present along the shorelines of eastern Lake Sakakawea, the thickness of the Upper Horseshoe Valley till ranges from two to five metres (Millsop, 1985, p. 61). It is exposed at stations 51 and 52, where it is the dominant bank lithology. Another exposure of this till was studied at station 60 and along a shoreline bank approximately 200 m northeast of station 60.

Fractures

General: The Upper Horseshoe Valley till can be distinguished from a distance by its characteristic large-scale "columnar jointing pattern" (Millsop, 1985, p. 61) which is the result of large intersecting vertical fractures (Fig. 21). Active bank failure in the form of high-angle slides and topples occur readily along these large vertical planes of weakness. Other than the large joints, this till unit appears more homogeneous than the underlying Upper Medicine Hill till which contains more sand, silt, and gravel lenses and more boulders and cobbles.

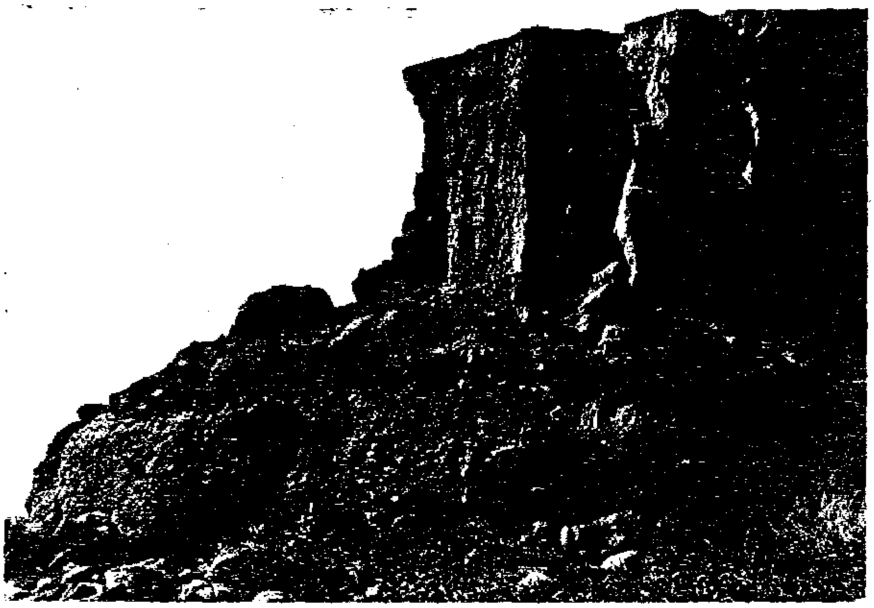


Figure 21. Upper Horseshoe Valley Till with Strong Columnar Jointing Overlying Upper Medicine Hill Till, Station 51.

Horizontal Frequencies: Horizontal and vertical fracture frequencies were measured in the Upper Horseshoe Valley till at stations 51 and 52. The horizontal frequencies of just less than one fracture/metre for both stations are the lowest frequencies obtained for any of the geologic units examined (Table 4). Most of the horizontal fractures in this unit were weakly developed. These low horizontal frequencies are consistent with other Upper Horseshoe Valley exposures observed in this area which are dominated by large well-defined vertical fractures (Fig. 8).

Vertical Frequencies: Although vertical fractures in the Upper Horseshoe Valley till are large and well-defined, they are relatively widely-spaced compared to the other units. The average vertical fracture frequency at stations 51 and 52 is just over two/metre (Table 5). These values are typical of the low fracture frequencies in other Upper Horseshoe Valley till banks in this area.

Lengths: High-angle fracture lengths in the Upper Horseshoe Valley till were measured at stations 51, 52, and 60 and at one other shoreline bank, approximately 200 m northeast of station 60. Average lengths at these sites (Table 6) are considerably longer than those in the Upper Snow School and Upper Medicine Hill tills (Table 6). Again, like the other geologic units, the standard deviations are relatively high, reflecting a wide variation of fracture lengths at each site (fractures measured in this till ranged from 10 to over 700 cm in length). Most of the fractures were between 30 and 100 cm long; however, the number of fractures over 100 cm was much higher in this till (Appendix VII).

Orientations: The majority of the fractures measured in the Upper Horseshoe Valley till at stations 51 and 52 had vertical or near-vertical dips and the overall dispersion of strike directions was large

(Fig. 22). There are also two distinct high-angle orthogonal fracture sets, a NE-SW set with an approximate orientation of 28° and a NW-SE set with an approximate orientation of 150°.

In the area of station 60, 56 most of the Upper Horseshoe Valley till fractures are also vertical and there are two distinct vertical fracture sets oriented N-NW to S-SE at approximately 152°, and NE-SW at approximately 35° (Fig. 23).

The distribution of fracture orientations in the Upper Horseshoe Valley till are similar at both of these areas. Both data sets contain mostly vertical and near-vertical fractures and both indicate the presence of vertical and nearly orthogonal fracture sets oriented NW-SE and NE-SW. The large columnar jointing pattern seen in this till is formed by the intersection of these orthogonal sets.

Other: Nearly all of the fractures in the Upper Horseshoe Valley till have rough surfaces and straight to irregular geometries. Gypsum, calcite, and clay coatings or fillings, and iron-oxide stains, were observed in few of the fractures, but the majority were free of mineral deposits. Surface markings, such as plumose structures, pits, or slickensides, were not observed on any fracture surfaces in this till (Appendix III).

Upper Snow School Formation

General

The Snow School Formation, which consists of upper, middle, and lower members, is the youngest of the three formations comprising the Coleharbor Group (Fig. 3). The lower member, exposed at stations 5 and7, consists of iron-stained conglomerate and flat-bedded and locally cross-bedded light brownish-grey to pale brown, poorly sorted dirty sand. Abundant lignite fragments are concentrated along bedding planes (Millsop,

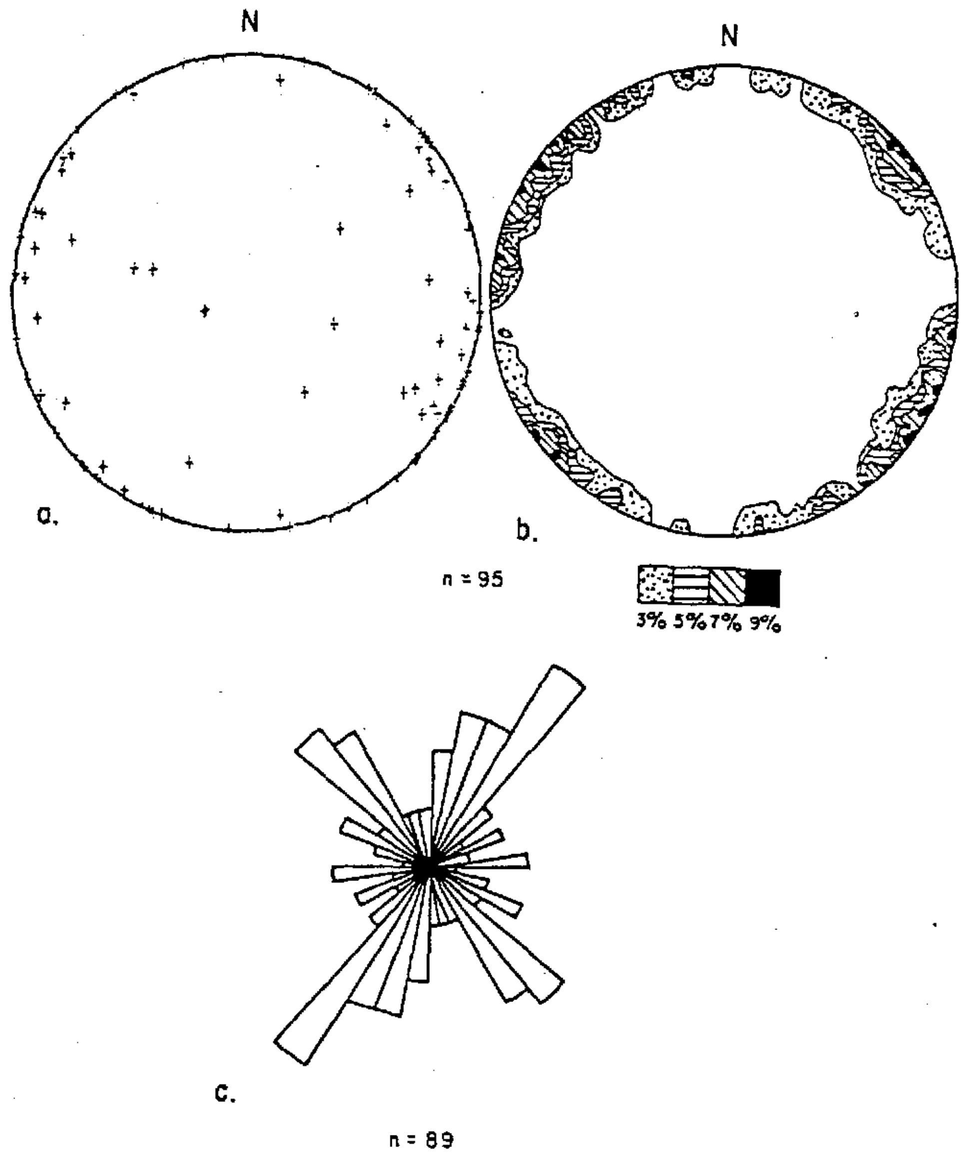


Figure 22. Upper Horseshoe Valley Till Fracture Orientations, Stations 51 and 52.

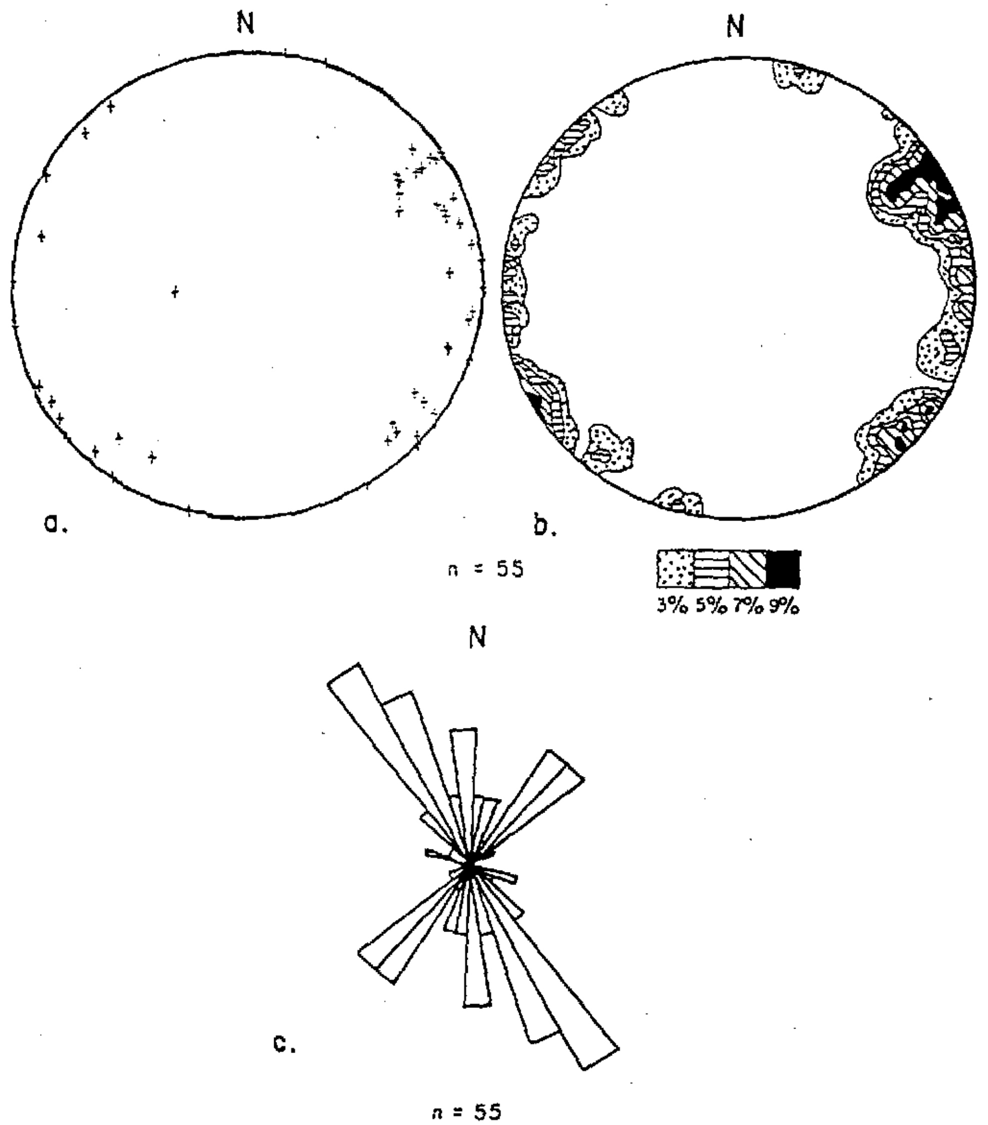


Figure 23. Upper Horseshoe Valley Till Fracture Orientations, Station 60.

1985, p. 62). At station 7, this member makes up the lower two to three metres of the bank and is very poorly-consolidated; thus it is susceptible to wave erosion during high lake levels. At station 5, the lower two to three metres of the bank is comprised of this lower member of the Snow School till. At this site it is moderately well-consolidated and, therefore, is more resistant to wave erosion and bank failure.

The middle member of the Snow School Formation is not represented at any of the bank recession stations, but it is exposed at several other locations along the shorelines of eastern Lake Sakakawea, and due to its reddish-brown color, it is an excellent marker bed where present.

The upper member of the Snow School Formation is a dense pebble loam (Millsop, 1985, p. 62) that locally displays a columnar jointing pattern similar to that in the Upper Horseshoe Valley till (Fig. 24). This unit is also interpreted to be a till (Millsop, 1985, p. 62). This and the Sentinel Butte Formation are the two most commonly exposed units along the shorelines of eastern Lake Sakakawea; it is the dominant lithology at stations 1, 3, 4, 6, and 7, and is one of the two dominant lithologies, along with underlying Sentinel Butte Formation, at stations 55, 56, and 57. The Upper Snow School till is as much as six metres thick in this area and is typically overlain by the Oahe Formation, a Holocene loess deposit.

This till is a light brownish-grey to pale olive pebble loam that contains scattered boulders and cobbles and lenses of sand and gravel which are more abundant near the surface. The average sand-silt-clay fractions are about 26, 41, and 32%, respectively, (Millsop, 1985, p 63; Ulmer and Sackreiter, 1973). The higher silt content is an important criterion used to distinguish it from the Upper Horseshoe Valley till. Also, average density of this till is much higher than that of the Upper Horseshoe Valley till, but it is still slightly lower than the Upper Medicine Hill till (Millsop, 1985, p. 63).

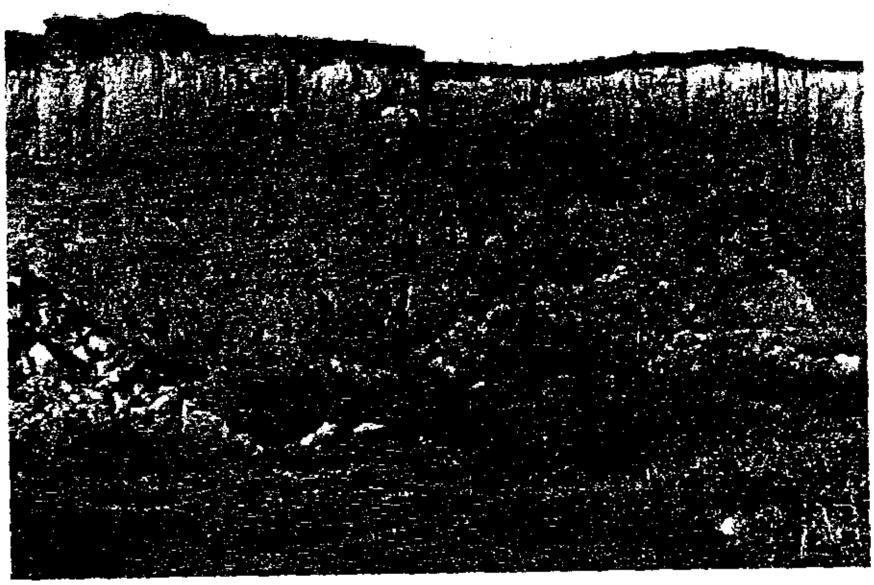


Figure 24. Columnar Jointing in Upper Snow School Till. Upper unit shown here is Upper Snow School till. Lower unit is Sentinel Butte Formation mudstone. (Fort Stevenson State Park)

Fractures

Horizontal Frequencies: Horizontal fracture frequencies measured in the Upper Snow School till at Lake Sakakawea State Park and stations 6 and 7 are low compared to those in the Upper Medicine Hill till and the Sentinel Butte Formation mudstone (Fig. 8). These low horizontal frequencies correspond well with visual observations of this till unit at other locations where it typically appears to be characterized by well-defined near-vertical fractures that are intersected by widely scattered and weakly developed horizontal discontinuities.

Vertical Frequencies: The range of vertical fracture frequencies in the Upper Snow School till (2.4/m at stations 6 and 7 to 4.5/m at station 4) (Table 5) is relatively small and indicates a tendency for higher vertical fracture frequencies than horizontal frequencies in this unit. Also, these frequencies tend to be lower than the vertical frequencies in the Upper Medicine Hill till and the Sentinel Butte Formation mudstone and slightly higher than the frequencies measured in the Upper Horseshoe Valley till and the Sentinel Butte Formation sandstone.

Lengths: Fracture lengths were measured in the Upper Snow School Formation at Lake Sakakawea State Park and at stations 6 and 7. (Table 6). The average length at these two areas is consistent(38 and 39 cm), but as with other units the variation of lengths for individual fractures, from less than 10 to over 300 cm, is large.

From casual observations, the overall appearance of the Upper Snow School till is similar to that of the Upper Horseshoe Valley till. Both of these tills have long vertical fractures forming a columnar jointing pattern. Despite this similar appearance, the average vertical fracture length of 39 cm for the Upper Snow School till is considerably lower than the overall average length of 82 cm determined for the Upper Horseshoe Valley till. The Upper Horseshoe Valley till contains more long fractures that are 100 to 500 cm in length, but most fractures in this till are between 30 and 100 cm; whereas in the Upper Snow School till most of the fractures are 20-80 cm long (Appendix VII). In contrast to these two tills, the Upper Medicine Hill till contains many oblique fractures and very few vertical fractures that are over 100 cm long; most of these fractures range from 20-60 cm in length.

Orientations: As in the Upper Horseshoe Valley till, most of the fractures in the Upper Snow School till at Lake Sakakawea State Park are vertical or nearly vertical. However, there is a large dispersion among strike directions (Fig. 25). Despite the high dispersion, two distinct vertical fracture sets can be identified from these data, a N-NE to S-SW set, with an approximate orientation of 18°, and an E-W set, with an approximate orientation of 86°.

The orientation data for Upper Snow School fractures at stations 6 and 7 indicate that in this area, at Lake Sakakawea State Park, there are mostly vertical or near-vertical fractures with high degree of directional dispersion (Fig. 26). One distinct vertical fracture set, oriented N-NW to S-SE at approximately 172°, can be clearly identified from these data, and another more weakly-defined and highly dispersed W-NW to E-SE trending set, with an approximate orientation of 111°, is also evident (Fig. 26). Neither of these fracture set orientations corresponds to the orientations of Upper Snow School till fracture sets identified at Lake Sakakawea State Park.

Other: Even though banks at stations 55, 56, and 57, in Fort Stevenson State Park are composed of the Upper Snow School till, which overlies the Sentinel Butte Formation, direct measurements of fractures could not be

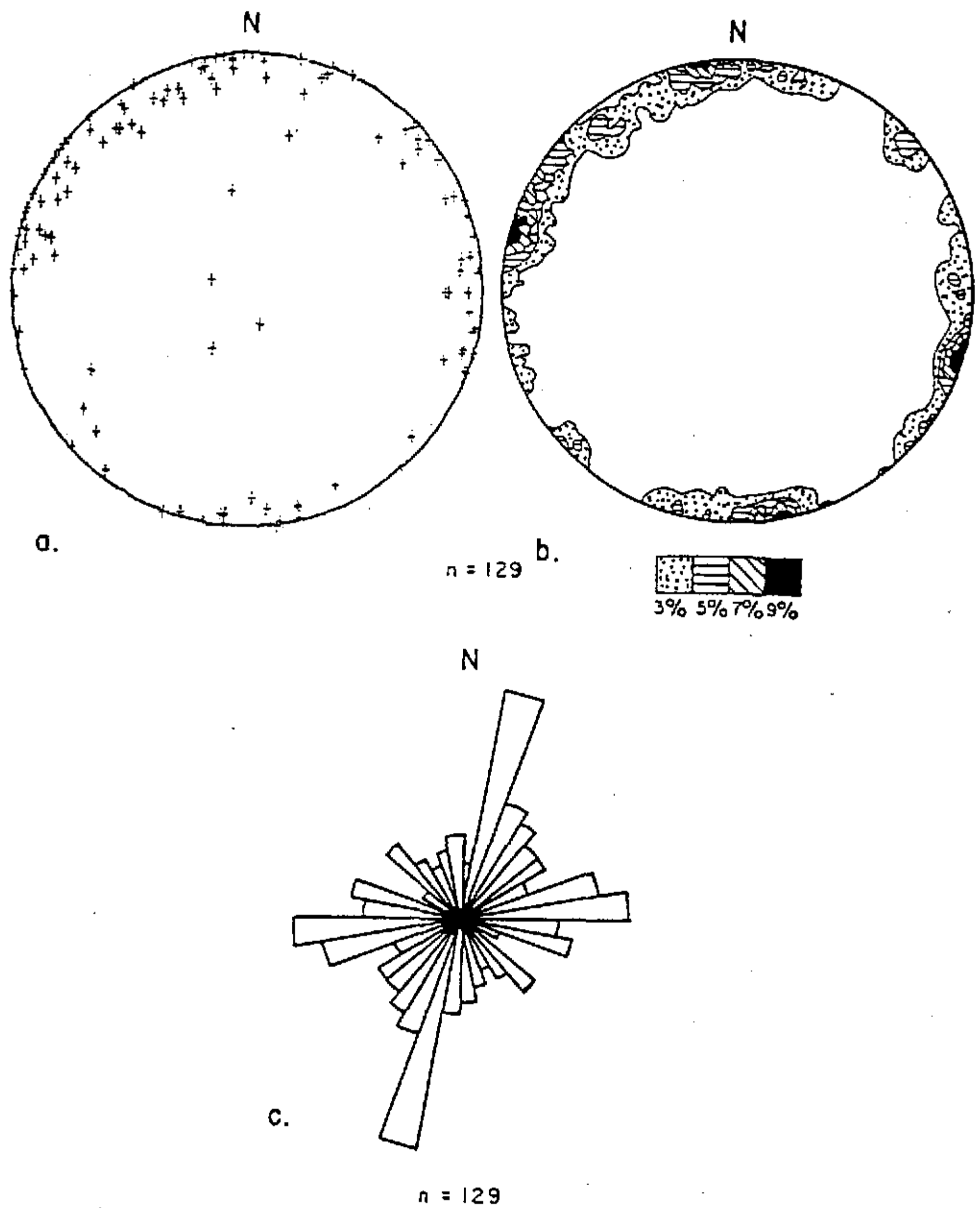


Figure 25. Upper Snow School Till Fracture Orientations, Lake Sakakawea State Park.

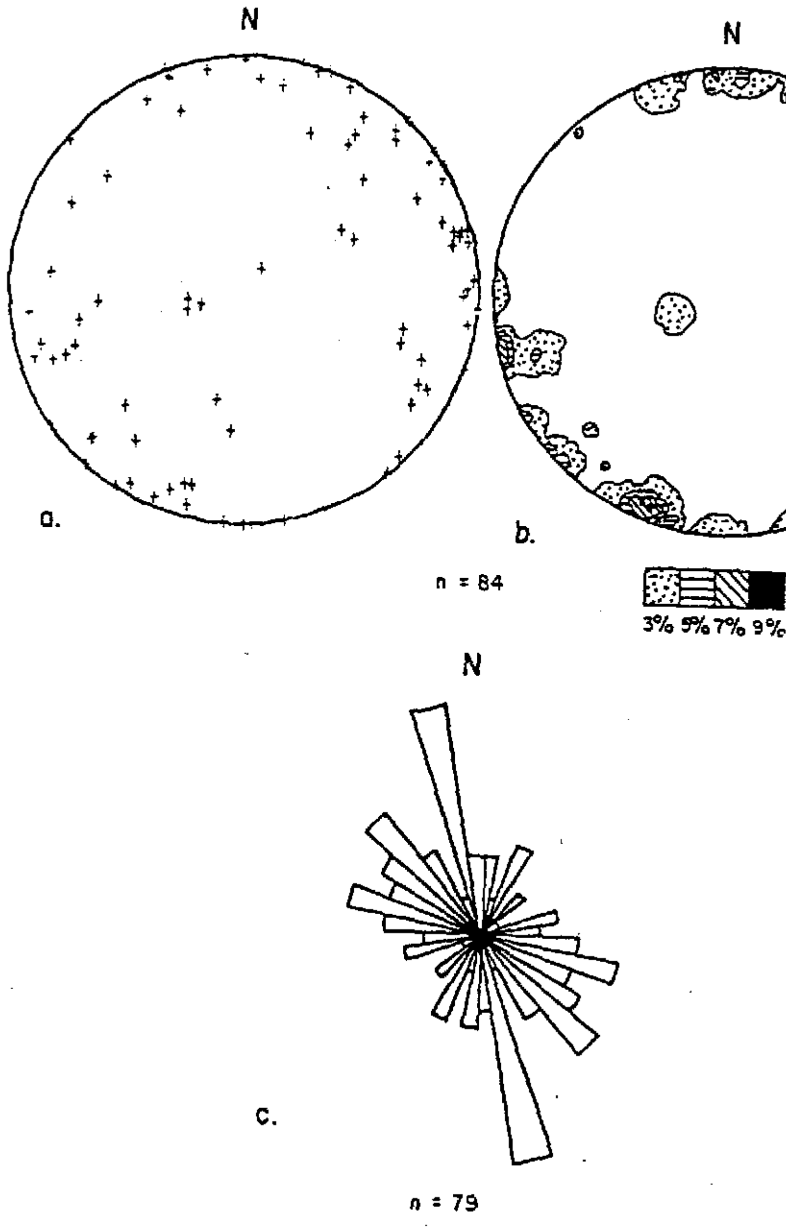


Figure 26. Upper Snow School Till Fracture Orientations, Station 6 and 7.

made for this unit in this area. This is because the exposures in Fort Stevenson State Park are too high above the beach level to access for detailed study. Visual observations do suggest similarities, though. The Upper Snow School till here also contains long straight vertical fractures which intersect, forming a columnar jointing pattern. And like the Upper Snow School till on the south side of the lake, this till, on the north side of the lake, appears to contain mostly vertical fractures and few horizontal discontinuities.

The fracture patterns in the Upper Snow School till are more similar to those in the Upper Horseshoe Valley till than those of the Upper Medicine Hill till. The Upper Snow School and Upper Horseshoe Valley tills are characterized by long intersecting vertical fractures which form a columnar jointing pattern (Fig. 8). Also, in contrast to the fracture patterns of the Upper Medicine Hill till, there are very few oblique and horizontal fractures. And like the fractures in the Upper Horseshoe Valley till, fractures in the the Upper Snow School till tend to be straight with rough or matte surfaces free of mineral coatings. The difference in fracture patterns between the Upper Snow School and Upper Horseshoe Valley tills is higher average vertical length for the Upper Horseshoe Valley till and a higher dispersion of fracture orientations for the Upper Snow School till.

Oahe Formation

General

The Oahe Formation is a Holocene, light grey to dark grayish-brown, and poorly sorted wind-blown silt (loess) deposit (Millsop, 1985, p. 63). It is the youngest and the highest stratigraphic unit in this study area (Fig 3). Textural, physical, and compositional analyses are reported by Millsop (1985, Appendix A).

This unit is discontinuous and where exposed it is up to 100 cm thick. The bank tops at many of the bank recession stations are underlain by a thin discontinuous layer of Oahe loess; however, the only significant accumulations are at stations 1, 3, 4, and 52 where a persistent 10-100 cm thick layer is exposed. Because it is not the dominant bank-forming lithology at any of the bank recession stations, it is relatively unimportant with regard to bank recession.

Fractures

This loess unit exhibits strongly developed, closely spaced vertical fractures which extend through the entire unit and intersect, forming a columnar jointing pattern (Fig. 8). Despite the strong development of such vertical fractures, it appears to be more resistant to erosion than the underlying tills (Fig. 27). This is due to the extensive root development which holds the sediment together.

Fracture frequencies were measured in the Oahe Formation at stations 1, 3, and 4 in Lake Sakakawea State Park. Horizontal fractures are weakly developed, short, and widely spaced (Table 4). The well-developed vertical fractures that extend through it are more closely spaced, with frequencies of about 10/m (Table 5).

Because most of the fractures in the Oahe loess are cut off by extending through the entire unit and into the underlying till or up to the ground surface, the ends of most fractures cannot be seen, and therefore, their complete length cannot be determined. Due to these circumstances, the average fracture lengths were not determined for this unit. Most of the incomplete fractures ranged in length from 10 to 60 cm.

Figure 27. Relatively Resistant and Densely-Rooted Oahe Formation Overlying Upper Snow School Till; Lake Sakakawea State Park.

Bank-Top Fractures

Many of the banks along the shorelines of Lake Sakakawea are failing along large vertical fractures that have formed parallel to the bank edge. Bank-top fractures examined at each of the bank erosion stations are the surface expression of these large cracks (Fig. 28). At each of the erosion stations an attempt was made to evaluate the size, abundance, location, and orientation of these fractures (Appendix IV) to assess possible correlations of the degree of their development with bank lithology, geometry, and recession rates.

Most of the bank-top fractures examined were oriented roughly parallel to the bank faces and were within two metres of the bank edge. The few bank-top fractures not parallel to the bank edge were smaller and extended only as far as intersecting bank-parallel fractures. The variation in abundance and size of the bank-parallel fractures from site to site seems to be the most significant characteristic of these fractures. These variations may be associated with bank height, bank lithology, and the direction and size of primary fractures in the bank material. The advanced development of bank-top fractures at some sites is undoubtedly related to bank instability.

The density of bank-top fractures ranged from 0 to 19 per 10 m transect, average lengths ranged from about two to six metres, and the longest fractures were over 15 m long (Table 7). Banks composed of the Upper Snow School and Upper Horseshoe Valley tills, which contain more long vertical fractures, have the highest bank-top fracture densities and fracture lengths whereas banks composed of the thickly rooted Oahe loess and the horizontally fractured and Upper Medicine Hill and Sentinel Butte units tended to have fewer and smaller bank-top fractures. These data do not suggest a relationship between the maximum distance of bank-top fractures from the bank edge and bank geometry or lithology.

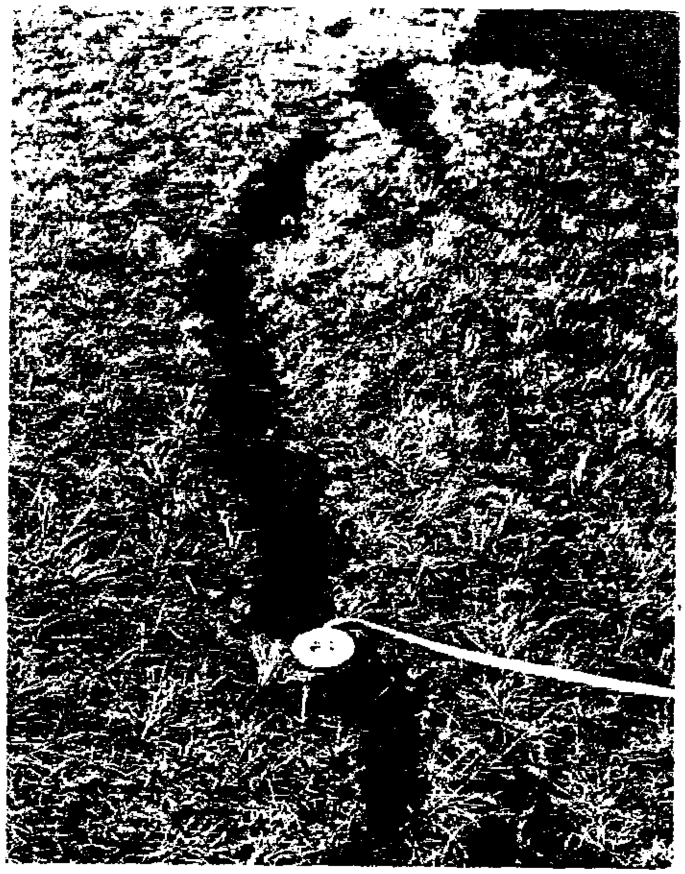


Figure 28. Bank-Parallel Bank-Top Fracture, Lake Sakakawea State Park.

TABLE 7

BANK-TOP FRACTURE CHARACTERISTICS

Station	Underlying Lithology	Density #/10m	Mean/Max Length cm	Max Distance metres
1	oah	1	2.5/3	.75
3	oah	1	2.0/2	.78
4	uss	5	2.3/3	1.6
6/7	uss	8	5.8/9	1.6
56	uss	10	-----	1.7
57	uss	14	-----	2.0
52	uhv	19	5.6/15	1.9
51	uhv	15	3.8/17	4.0
60-62	uhv	5	3.5/5	2.7
2	sb	9	5.2/15	1.8
50	sb	5	4.0/4	.75
54	sb	0	------	----
53	uhm	2	------	----
58	uhm	3	6.3/8	1.4
59	uhm	3	4.0/4	1.4

EXPLANATION

oah- Oahe Formation

uss- Upper Snow School till

uhv- Upper Horseshoe Valley till

umh- Upper Medicine Hill till

sb- Sentinel Butte Formation

DISCUSSION

Fracture Genesis

General

Although much can be inferred about the origin of the Lake Sakakawea fractures from the data collected, more information regarding cross-cutting relationships, displacement directions, surface markings, and spatial distribution is still needed before some of the fracture patterns in this area can be explained fully. But in order to gain a better understanding of the variations in the fracture patterns being described, the available data should be used to infer as much as possible about their origins.

Fractures represent strain accommodation by brittle failure when a material is subjected to tensile or shear stresses associated with processes such as crustal uplift, crustal compression, volume changes (during changes in moisture, temperature, or chemistry), unloading, or subglacial deformation.

Determining what processes are responsible for a given fracture or a given set of fractures is difficult. Most earth materials have been subjected to more than one fracture-forming process. And while fractures formed by different processes will often have the same characteristics, fractures formed by the same process in different materials will often display different characteristics.

This section includes a brief discussion of some of the fracture-forming mechanisms that have likely influenced tills and bedrock in this study area. More complete discussions of fracture-forming mechanisms are found in Pollard and Aydin (1988), Connell (1984), Boulton and Paul (1976), Price (1966), and Hodgson (1961).

Regional Stress

Regional fracture sets are the result of forces that influence large areas of the earth's crust over relatively long periods. Some proposed sources are wide-spread crustal unloading, uplift, subsidence, or shortening, plate motion, and possibly earth tides.

Fractures that form due to regional stress fields can usually be grouped into sets with distinct orientations traceable over wide geographic areas independent of variations in bedrock structure and lithology, and they often persist through great stratigraphic thicknesses, representing geologic time intervals of tens and even hundreds of millions of years (Stauffer and Gendzwill, 1987; Holst, 1982; Babcock, 1973; and Hodgson, 1961). In many cases, vertical fractures from regional sets can be seen extending across horizontal discontinuities including fractures, bedding planes, and even major lithologic boundaries (Stauffer and Gendzwill, 1987; Grisak and Cherry, 1975; and Secor, 1965).

Experimental results (Daubree, 1879; Mohr, 1900, <u>in</u> Pollard and Aydin, 1988) and field relationships (Bucher, 1920, <u>in</u> Pollard and Aydin, 1988; Boulton and Paul 1976, Price, 1966) indicate that fractures resulting from shear stress induced by compressive forces tend to form a pattern of conjugate fracture sets with an acute intersecting angle bisected approximately by the direction of the maximum principal stress (σ_1) (Pollard and Aydin, 1988; Secor, 1965). Fractures formed due to shear stress or faults (Pollard and Segall, 1987) are also recognized by displacement across the fracture boundary and by slickensided surfaces, if preserved.

Regional extensional fractures ("joints", Pollard and Segall, 1987) tend to be straight and rectangular in shape and are usually oriented perpendicular to bedding in layered sediments (Pollard and Aydin, 1988; Fookes and Denness, 1969). Plumose surface structures and rib marks are characteristic of joints (Pollard and Aydin, 1988; Price, 1966). However, these structures are seldomly preserved well on near-surface joints. Holst and Foote (1982) and Babcock (1973) reported seeing only a few of these surface structures after examining many thousands of joints.

Price (1966) contends that extensional fractures (joints) are more irregular and tend to terminate at lithologic boundaries, whereas fractures formed by shear stress (faults) have more planar surfaces and tend to cut across lithologic boundaries. Although this may be true for tensional joints formed near the earth's surface, recent studies (Olsen and Pollard, 1988) suggest that straight extensional fractures can form at depth under large confining pressures if tensile stress aided by pore water pressure exceeds the magnitude of the least principal stress (σ_3) along the boundaries of void spaces or other incompatible flaws. Failures of this type propagate parallel to the direction of σ_1, resulting in the formation of straight fractures.

Although many regional fracture sets are reported to be unrelated to area tectonic structures, such as the Williston Basin (Stauffer and Gendzwill, 1987) and the Michigan Basin (Holst, 1982), others do appear to be related to structures. Holst and Foote (1982) and Babcock (1973) reported regional orthogonal joint sets parallel and perpendicular to a series of parallel fold axes. Some of the regional joint sets in the Appalachian Mountains are consistently parallel to the direction of maximum compression associated with regional bedrock structures (Engelder and Geiser, 1980).

Regional joint sets, consisting of one or two vertical orthogonal systems, are widely reported in flat-lying sedimentary rocks of the North American midcontinent (Peter and others, 1988; Stauffer and Gendzwill, 1987; Holst, 1982; and Babcock 1973).

In central Alberta, there are two orthogonal joint systems, consisting of four well-defined vertical regional joint sets. They are interpreted to be the result of crustal extension related to epeirogenic uplift and from the regional folding that occurred during the Laramide orogeny (Babcock, 1974).

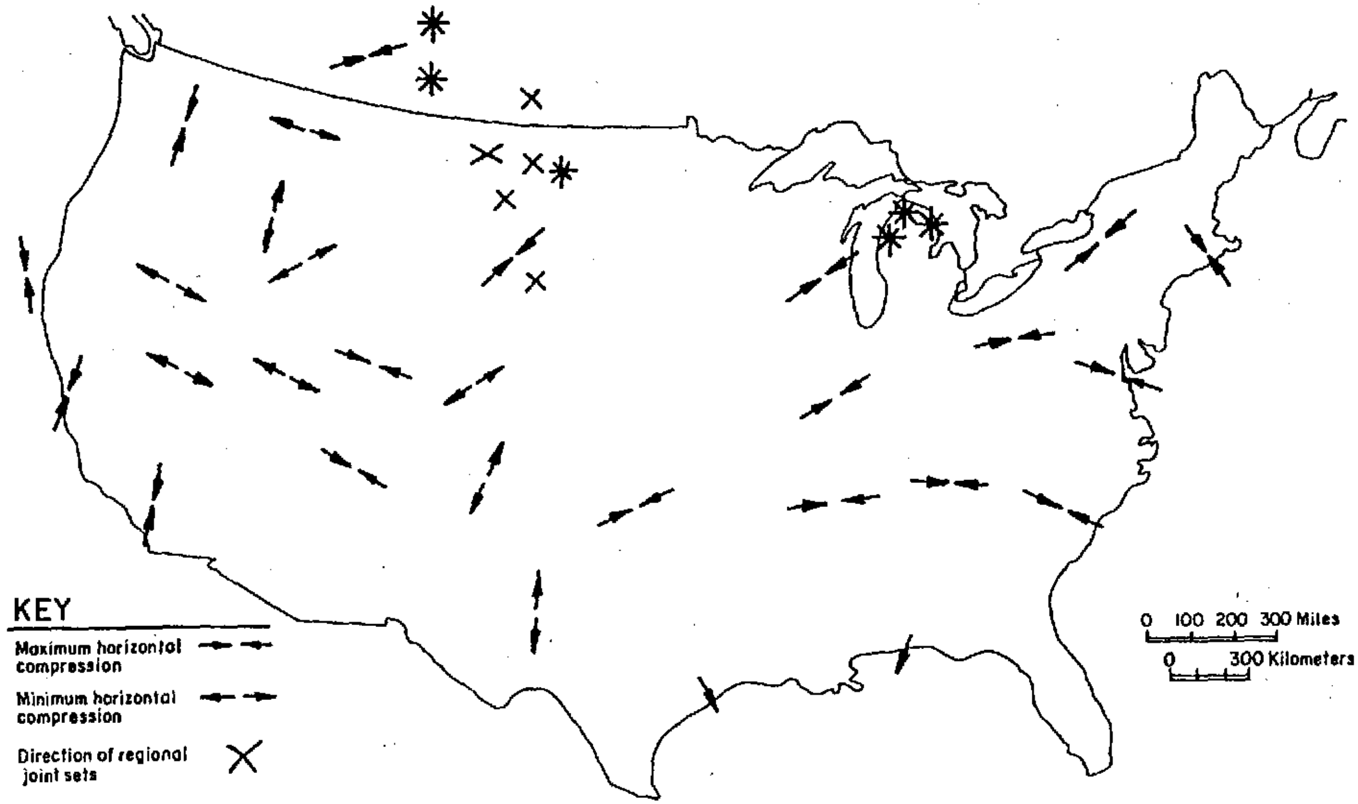
Holst (1982) contended that one of the two orthogonal joint systems in the Michigan Basin area is related to plate motion which is parallel to the direction of maximum horizontal stress in that region. This system consists of joint sets oriented parallel and perpendicular to this direction; these sets are also parallel and perpendicular to a series of parallel folds in this region. Stauffer and Gendzwill (1987) have made a similar interpretation for the regional orthogonal joint system in the northern great plains.

In each of these cases, vertical joint sets are oriented parallel and perpendicular to the direction of maximum horizontal stress in the earth's crust. Figure 29 shows the direction of maximum horizontal compression in the earth's crust for various locations in North America (Zoback and Zoback, 1980) and the directions of major regional joint sets determined in these areas.

Stress Relief

Vertical or lateral unloading due to erosion can cause tensional or shear stresses that lead to fracturing. Tensional fractures, resulting from stress release, form parallel to an exposure face or erosional surface. When these fractures form near an exposure face, they typically have a rough surface and a non-planar geometry (Fookes and Denness, 1969). Shear stress large enough to cause failure may occur when rapid erosion of material and subsequent stress relief in one direction increases the state of differential stress (Nichols and others, 1986).

Fookes and Denness (1969) and Kazi and Knill (1973) reported that vertical fracture sets, consisting of curved and irregular-shape fractures oriented parallel to bluff faces, were present at nearly all bluff exposures that they studied, regardless of bluff orientations. They



<u>Figure 29</u>. Directions of Crustal Stress and Selected Regional Vertical Joint Sets in the United States, (modified from Zoback and Zoback, 1980).

interpreted these to be the result of stress relief parallel to the eroding banks. Also, the density of these fractures slowly increased with time (Fookes and Denness, 1969).

Closely spaced horizontal fractures that are common in many overconsolidated tills usually form during rapid deglaciation. If high pore water pressures and subsequent low effective strengths are maintained in these impervious materials during deglaciation, tensional forces associated with overburden removal can result in failure (Boulton and Paul, 1976).

Horizontal fractures parallel to bedding planes are common in many flat-lying bedded sediments affected by vertical unloading. Cretaceous sediments of southeast England, influenced by vertical unloading, contained horizontal fractures only where well-developed horizontal bedding was present (Fookes and Denness, 1969). Evidently inherent discontinuities separating these beds served as natural planes of weakness.

Conditions favorable for the formation of horizontal fracture zones were found in the Pierre shale in South Dakota. In situ hydrostatic stress conditions were measured below 15 m deep; however, in areas affected by rapid lateral or vertical erosion, ratios of horizontal to vertical stress were high enough for failure to occur along low-angle shear planes. Additional horizontal tension cracks form when this process is combined with the weakening effects of weathering (Nichols and others, 1986).

Volume Change and Weathering

Many chemical and physical weathering processes influence rock and soil located near the earth's surface. Weathering processes associated with volume change are especially effective in creating new fractures and exploiting pre-existing zones of weakness, thus causing the fracture density near the surface to increase with time (McGown and others, 1974;

Fookes and Denness, 1969). Fractures are formed during volume changes associated with wetting and drying or freezing and thawing cycles and because of chemical changes such as leaching or cation exchange with clay minerals. As moisture is lost from a fine-grained sediment shrinking occurs and associated tensional stress is accommodated by fracturing (Kindle, 1917; Lachenbruch, 1962; Sleeman, 1963; Corte and Higashi, 1964). Sediments containing double-layered clay minerals are affected by drying to a greater extent. As water is removed from the inter-layer bonds of these clay molecules, their size may decrease as much as 20 to 30%, depending on the clay minerals present in the sediment (Post, 1981).

During desiccation, randomly oriented fractures develop perpendicular to a drying surface to form a four- to six-sided polygonal network, if the material is homogeneous and no outside differential stresses are involved (Corte and Higashi, 1964; Lachenbruch, 1962). These tension joints are straight and rectangular in shape and are usually long in the direction normal to the drying surface (Pollard and Aydin, 1988). The formation of near-vertical joints intersecting to form polygonal surface patterns has been observed in both flow and lodgement tills during rapid drying after deglaciation (Boulton and Paul, 1976).

Stresses associated with water freezing in sediment voids also can be large enough to cause failure (Fahey, 1983). These stresses result from increases in volume as water turns to ice and by suction from the attraction of water to the freezing front (Chamberlain, 1981). This process is more effective at exploiting pre-existing zones of weaknesses than creating new fractures.

In addition to the above processes, chemical weathering can influence fracture formation by causing a change in volume. Oxidation of clay in fracture zones in the Pierre shale by circulating groundwater is partly responsible for its increased instability (Nichols and others, 1986). Volume loss associated with carbonate leaching may be responsible for well-developed contraction joints in pre-Illinoian tills of eastern

Iowa (Connell, 1984, p. 24). Also, cation exchange, involving smectites, can influence the swelling potential of clay-bearing sediments. Swelling potential has been found to be directly proportional to the density of desiccation fractures (Post, 1981).

Subglacial Deformation

Oblique and conjugate sets of vertical fractures are commonly observed in subglacial tills (Connell, 1984; Derbyshire and Jones, 1980; McGown and Derbyshire, 1977; Boulton and Paul, 1976; and Kazi and Knill, 1973) leading to the speculation that their formation is associated with subglacial deformation. Because glacial ice is unable to withstand shear stress in excess of 150 KPa (Paterson, 1981, p. 86) it is thought that the mechanical properties of ice will limit the amount of basal shear stress that can be transmitted to subglacial sediment. However, due to large fluctuations in pore water pressures and consolidation conditions beneath temperate glaciers, it is conceivable that stress conditions conducive to brittle deformation could occur under conditions of low effective stress. For example, the stress conditions beneath the Breidamerkurjokull in Iceland exceeded the strength of the sediment below the ice in a narrow zone near the ice/ground interface only. In this zone, the effective strength of the sediment was lower than normal because of high pore water pressures built up between the relatively impermeable ice and underlying sediment (Boulton and Paul, 1976).

Pressure associated with compressive flow, which occurs when the flow of ice is directed into a ground surface or where velocity or loading conditions suddenly change, may be great enough to cause deformation (Banham, 1975; Shaw, 1979). Nye (1952) determined that planes of maximum shear at the base of a glacier during compressive flow are oriented either perpendicular to the direction of flow or parallel to the ice surface.

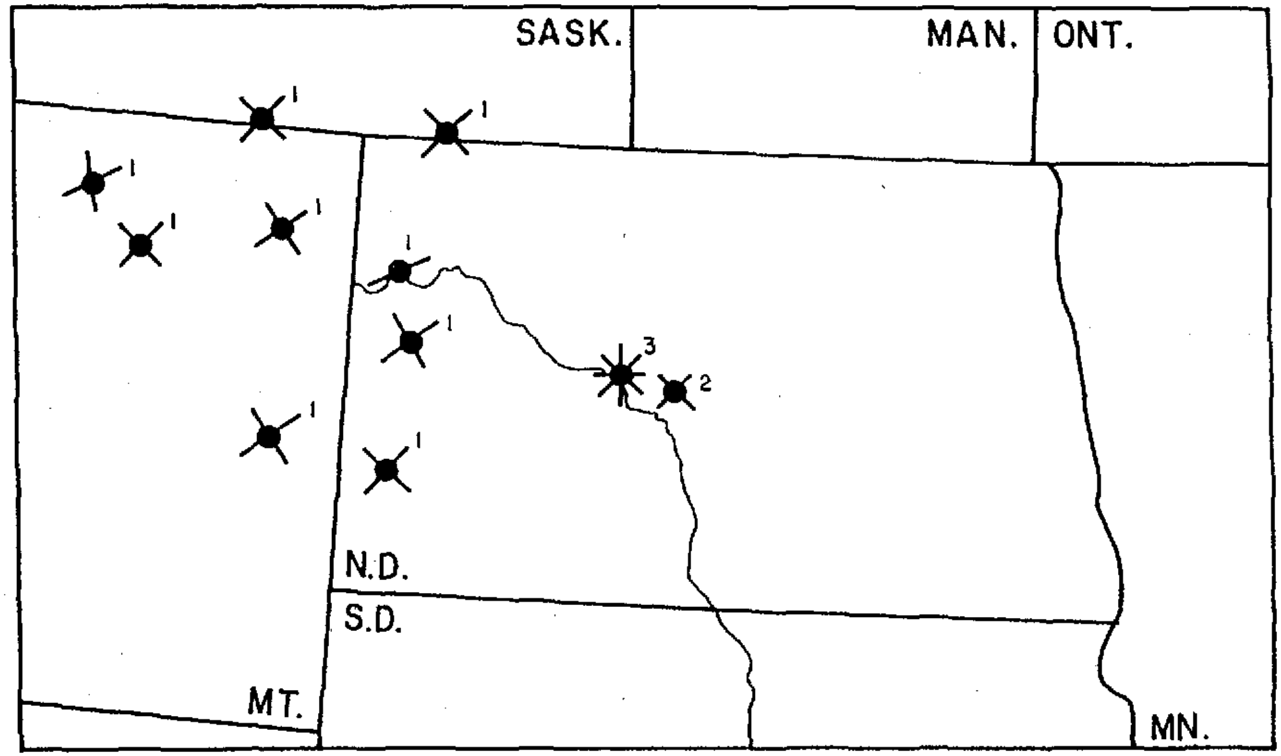
Boulton and Paul (1976) found slickensided horizontal fractures in till beneath the Nordenskioldbreen, Svalbard, along with conjugate sets of near-vertical fractures separated by a 65° angle and bisected by the direction of ice flow. Similar conjugate vertical fracture patterns described by McGown and Derbyshire (1977) and Kazi and Knill (1973) were also attributed to subglacial deformation.

Genesis of Lake Sakakawea Fracture Patterns

Sentinel Butte Formation: Although the fracture frequency and fracture lengths in the Sentinel Butte Formation vary from site to site, depending on lithologic and structural differences, fracture orientations are consistent throughout this study area. Fractures in each of these subunits are nearly horizontal and parallel to bedding or are nearly vertical. In the Sentinel Butte mudstone and sandstone there are four vertical sets at approximately 45° to each other that are consistently present. At each of the four areas studied, two to four of these vertical fracture sets make up one or two orthogonal fracture systems. Because of their straight geometry, the lack of surface textures or displacements indicating shear, and the consistent orientations, these are interpreted to be regional extensional joints.

Two vertical orthogonal joint sets trending NW-SE and NE-SW persist throughout western North Dakota, eastern Montana and Wyoming, and southern Saskatchewan and Alberta (Stauffer and Gendzwill, 1986; Erikson, 1970; Stone and Snoeberger, 1977) (Fig. 30). The average azimuth of these sets is (49°, and 139°), and in this region they exist in all types of bedrock and glacial and alluvial sediments, ranging in age from Cretaceous to the present (Stauffer and Gendzwill, 1986). A similar orthogonal vertical joint system was found in coal seams at the Falkirk coal mine, approximately 25 kilometres southeast of Riverdale, North Dakota (Rehm and others, 1980).

The consistently oriented fracture sets found throughout this region are interpreted to be regional extensional-type joints resulting from the combined effects of a crustal stress with NE-SW maximum



<u>Figure 30</u>. Regional Vertical Joint Set Orientations, Northern Great Plains. (1 = data from Stauffer and Gendzwill (1986), 2 = data from lignite layers in the Falkirk mine (Rehm and others, 1980), 3 = data for eastern Lake Sakakawea from this study.

horizontal compression (Zoback and Zoback, 1980) and crustal extension associated with regional uplift. At least 600 metres of uplift has occurred in this region since the Late Cretaceous when seas last covered this area (Stauffer and Gendzwill, 1986). A similar interpretation has been made regarding the origin of NW-SE and NE-SW orthogonal joint systems that persist throughout the entire northern part of the Michigan Basin (Holst, 1982).

This interpretation does not account for the formation of the N-S and E-W sets of joints that also prevail in this study area. Holst (Michigan Basin, 1982) and Babcock (Alberta, 1973) both described similar regional joint patterns consisting of two orthogonal systems. Although they presented possible explanations for the formation of the NW-SE and NE-SW orthogonal sets, neither speculated on the origin of the N-S and E-W trending sets.

Many minor structural trends in the Williston Basin, such as the Nesson Anticline, the Billings Anticline, and the Little Knife Anticline, trend almost directly N-S (Gerhard and others, 1982). The N-S and E-W joint sets may comprise an orthogonal system that is related to a local tectonic structure, possibly a N-S trending fold. Unfortunately, the bedrock structure in the eastern part of the Williston Basin, which this study area overlies, has not been well defined.

Based on what is currently known about regional joints in western North Dakota, orthogonal sets of NW-SE and NE-SW vertical joints are likely to occur in the Paleocene bedrock throughout the Lake Sakakawea region. The N-S and E-W sets, however, may be a local orthogonal system, possibly related to a relatively small-scale bedrock structure. More study is needed to define the extent of this system.

Although four regional joint sets are well-defined in this area, there is still a considerable variation of vertical fracture orientations. This can be explained by fractures resulting from other processes, including lateral tension following bank erosion and desiccation. A comparison of fracture geometries and orientations might be used to distinguish between different types of fractures.

Horizontal fractures in the Sentinel Butte Formation are all parallel to bedding. The most likely cause of these horizontal fractures is vertical tension associated with vertical unloading during deglaciation or overburden erosion. Horizontal fractures are common in uplifted overconsolidated sediments, especially if bedding planes are well-developed and parallel to the eroding surface (Fookes and Denness, 1969).

Upper Medicine Hill Till: The Upper Medicine Hill till consists of closely spaced, short, straight, and near-vertical fractures (dipping 60-90°), closely spaced straight and curved horizontal fractures (dipping 0-10°), and straight and curved oblique fractures (dipping 10-60°). The complicated fracture pattern in this till is probably the result of several fracture-forming processes including subglacial deformation, regional crustal stress, unloading, and desiccation.

Some of the fracture characteristics in the Upper Medicine Hill till are similar to characteristics in tills of Iceland, Great Britain, Ireland, and the eastern United States that have been interpreted to be the result of subglacial deformation (Derbyshire and Jones 1980; Boulton and Paul, 1976; Banham, 1975; Kazi and Knill, 1973;). Fracture patterns consisting of straight near-vertical conjugate fracture sets separated by an acute angle and intersected by curved near-horizontal and oblique fractures in these tills were attributed to shear-stress deformation during compressive ice flow, under conditions of low confining pressure and high pore water pressure. Also noted for these tills, was that the direction of ice flow, which presumably corresponds to the direction of maximum horizontal stress during deformation, bisects the acute angle separating these sets.

The characteristic high density, deformed silt lenses, and the low stratigraphic position suggest that the Upper Medicine Hill till may have been deposited subglacially or was overridden and deformed by later glacial advances. In this till it is common to see short, straight, and near-vertical fractures that intersect or terminate at larger curved or straight subhorizontal fractures (Fig. 8). This pattern is similar to the fracture patterns described by the above authors; however, the orientations of the dominant vertical fracture sets (Fig. 18-20) do not reflect a pattern of conjugate sets arrayed around the presumed direction of ice flow in this area, which is from the north (Clayton et al., 1980). Instead, the vertical fracture sets (Fig. 18-20) show an E-W and N-S orthogonal system at station 53. At stations 51 and 58/59 there are three sets separated by 45° angles. Therefore, fracturing due to subglacial shear stress is probably not responsible for the formation of most of the vertical fractures in this till.

The curved oblique and subhorizontal fractures, however, may be related to subglacial shear stress during compressive flow. Calculations of probable stress fields at the base of glaciers during such flow (Nye, 1952) suggest that subhorizontal and oblique shear planes would form slightly curved paths convex toward the direction of flow. It is also possible that these fractures are result of tensional stress or shear stress associated with rapid loading and unloading events during glaciation (Lafluer, 1980; Nichols and others, 1986). More fracture measurements and an attempt to isolate types of fractures based on geometry and surface markings are needed to confidently determine if the origin of some of these fractures is related to subglacial deformation. More detailed information on ice flow directions and till fabric would also be helpful.

Other fracture-forming processes, including regional stress, dewatering during deglaciation, recent desiccation, and lateral unloading associated with bank erosion, have also affected this till, and these certainly must have contributed to the variation of fracture types and orientations observed.

Stauffer and Gendzwill (1986) and Grisak and Cherry (1975) both reported that orientations of vertical fractures in Pleistocene tills and other younger sediments in this region commonly correspond to the orientations of regional joint sets in the underlying bedrock. This implies that processes related to the formation of these regional joint sets have continued up through modern times or that bedrock fractures tend to propagate up into overlying sediments.

There are two or three dominant vertical fracture sets in the Upper Medicine Hill till at each of three sites studied. The orientations of these sets do not correspond from site to site; however, the orientation of each of these sets is close enough to one of the four regional bedrock joint sets that it is possible that they are the result mainly of processes also responsible for regional joint sets observed in the Sentinel Butte bedrock (Fig. 18-20 and 10-14).

Upper Horseshoe Valley and Upper Snow School Tills: The Upper Horseshoe Valley and Upper Snow School tills, which can easily be distinguished from the Upper Medicine Hill till from their characteristic columnar jointing pattern, show little evidence of subglacial deformation. Most of the fractures in these tills are vertical, have a straight to slightly irregular geometry, and have rough or matte surfaces. Horizontal and oblique fractures are poorly defined and are widely scattered to absent.

Although from a distance, a columnar jointing pattern consisting of long vertical fractures is apparent in both of these tills, these long fractures make up only a small percentage of the vertical fractures that can be seen close-up. The long vertical fractures probably form as pre-existing fractures are extended during desiccation and lateral unloading.

Because there are few horizontal discontinuities to disrupt propagation of vertical fractures, more long vertical fractures are able to form by this mechanism.

Vertical fracture sets are more tightly clustered in the Upper Horseshoe Valley till than in the Upper Snow School till. At both of the Upper Horseshoe Valley till sites studied there are strong NW-SE and NE-SW sets (Fig. 22 and 23). These are parallel to two of the regional joint sets in the underlying Sentinel Butte Formation; thus, most of fractures in the Upper Horseshoe Valley till may be related to regional forces that also have affected the bedrock. Other fracture-forming processes, such as desiccation and lateral unloading, continue to exploit pre-existing fractures and continue to form new fractures in this till.

In the Upper Snow School till there are also two distinct vertical fracture sets at both of the areas studied (Fig. 25 and 26). However, the directional dispersion of these sets is high and the orientations do not correspond between sites. Also, they do not correspond with any of regional sets in the Sentinel Butte bedrock. From close-up, the shorter vertical fractures in this till have a pattern similar to the fractures described in the Nordenskioldbreen lodgement till by Boulton and Paul (1976) where they were able to observe the formation of desiccation cracks immediately following deglaciation as drying progressed downward from the surface.

This till may have become fractured during or immediately following deglaciation due to horizontal extension associated with unloading or from rapid desiccation. If these fractures sets are the result of these processes, development of weakly defined preferred orientations could be controlled by site-specific confining conditions related to topography. Later desiccation, lateral unloading, and possibly regional crustal stress also continue to exploit pre-existing fractures and create new fractures.

Oahe Formation: The Oahe Formation is a wind-blown silt with strongly developed, closely spaced, and randomly oriented vertical fractures and widely spaced and poorly developed horizontal fractures (Tables 4 and 5). It also displays a columnar jointing pattern. This fracture pattern is the result of being exposed to continual shrinking and swelling associated with cycles of freezing and thawing and wetting and drying at the ground surface. A similar pattern of closely spaced vertical fractures is also present near the ground surface in some of the other lithologies.

Factors Affecting Fracture Length and Frequency

General

Variations in fracture patterns among sites can often be explained by differing fracture-forming processes. However, physical and lithologic properties are the most important factors controlling fracture length and density. For example, fracture orientations are consistent throughout the study area in all three of Sentinel Butte subunits, and each of these units presumably has been influenced by the same fracture-forming processes. Nevertheless, the average fracture frequencies and fracture lengths are considerably different in each lithology (Tables 4, 5, and 6).

Babcock (1973) and Stauffer and Gendzwill (1986) also noted strong correlations between fracture frequency and lithology during studies of regional jointing in Cretaceous and Tertiary sediments of southern Canada and the northern great plains of the U.S. They reported highest fracture frequencies in coal, followed by shale, with the lowest frequencies in sandstones. Fookes and Denness (1969) also found that the size and frequency of fractures were controlled by lithology and not fracture-forming processes.

Field observation at Lake Sakakawea suggest that physical and lithologic properties inherent to the bank materials, such as the abundance of horizontal discontinuities (bedding contacts and horizontal fractures), grain size, and compressibility and stiffness, are significant factors controlling fracture frequencies and average fracture lengths. Exposure to weathering is another significant factor; however, the magnitude of its effects are controlled by grain size and clay mineralogy.

Bedding and Horizontal Fractures

In rocks with similar properties, vertical fracture spacing and length is controlled by bedding thickness (Huang and Angelier, 1989; Pollard and Aydin, 1988; and Ladeira and Price, 1981). This relationship was also observed at Lake Sakakawea where the abundance and prominence of horizontal discontinuities appears to be the most significant factor affecting vertical fracture length and frequency.

Experimental evidence indicates that under confining conditions, joint propagation energy increases with joint length if all other factors remain constant; however, propagation may terminate when the joint reaches a stiffer or more compressible material, another discontinuity, or pore water pressure is dissipated (Segall, 1984). This explains why many fractures end at intersections with other discontinuities. Additional experiments (Segall, 1984) indicate that joint propagation energy is lower for closely spaced overlapping joints and propagation energy is even lower for short joints that are adjacent to longer joints. These observations may explain the commonly observed positive relationship of fracture spacing and fracture length.

In the Sentinel Butte Formation mudstone and the Upper Medicine Hill till vertical fractures are relatively short and are more closely spaced. Sentinel Butte Formation mudstone lithology is characterized by strong horizontal bedding. These lithologic boundaries and the horizontal fractures that have developed along them are responsible for limiting the vertical extension of many fractures in this unit. Strong horizontal fracturing in the Upper Medicine Hill till has had a similar effect. In both of these units many vertical fractures extend across horizontal structures; however, the overall effect has restricted average vertical fracture length. On the other hand, the Sentinel Butte channel sand and the Upper Snow School and Upper Horseshoe Valley tills, which contain fewer and more weakly defined horizontal discontinuities, have longer, more widely spaced vertical fractures.

Grain Size

Field observations indicate that fractures tend to be longer and more widely spaced in coarser-grained lithologies and shorter and more closely spaced in finer-grained lithologies. For example, in the Sentinel Butte Formation, the relatively coarse-grained channel sands have low fracture frequencies (Table 4 and 5); relatively high fracture frequencies and shorter fractures are found in the mudstone lithology. The smallest and most closely spaced fractures are in the lignite and adjacent carbonaceous clay-rich mudstone.

As discussed earlier, this relationship in the Sentinel Butte Formation is partly controlled by bedding, which is poorly developed in the channel sands but well-developed in the mudstone lithology. The influence of texture, however, may also be a factor. The influence of texture can be seen in the Upper Medicine Hill and Upper Snow School tills where there is a sharp contrast of higher fracture frequencies in the loamy till matrix and lower frequencies in the fine-sand and silt lenses. The lengths, however, are controlled by the size of any inclusions.

Grain size is thought to an important factor affecting fracture length and frequency because it is also related to consolidation properties and permeability. The effective strength of rock or sediment is reduced as pore water pressure increases (Secor, 1965). This is important because joint propagation energy increases with joint length (Segall, 1984), but termination of propagation can occur when pore water pressure along the joint face decreases enough for propagation to terminate. Because joint propagation energies can be maintained at a higher rate for longer periods in more permeable materials, it should be expected that longer and more widely spaced joints will form in these materials.

Consolidation

Consolidation properties also affect fracture frequencies and lengths. When stress is applied to a material containing void space some of the strain is accommodated by consolidation. The ability of a material to relieve stress by this means depends on the amount of void space available and the rate of consolidation, which is proportional to the permeability of the material (Das, 1985, Chapter 7). Therefore, poorly consolidated and relatively coarse-grained materials, such as the Sentinel Butte channel sand, have a greater ability to relieve rapidly applied stress (such as stress induced by glacial loading) through compression, whereas finer-grained facies, such as the Sentinel Butte mudstone, may be more likely to experience brittle failure, explaining the higher fracture frequencies in the mudstone and lignite.

The Sentinel Butte lignite facies and adjacent carbonaceous mudstones have the highest fracture frequencies of the lithologies studied. This is mainly because the lignites are weak and brittle, and the adjacent carbonaceous clay is impermeable and susceptible to fracturing during desiccation because of the high clay content.

Weathering

Fracture frequencies increase and average lengths decrease in rock and soils exposed to weathering. This process has a varying degree of influence depending on the lithology; generally fine-grained sediments and material containing expandable clays are affected to a greater degree.

In the fresh bank exposures at Lake Sakakawea fracture frequencies are highest near the ground surface and decrease downward to approximately one to two metres below the surface. Below this level fracture frequencies are nearly constant in any one lithology. This depth presumably represents the depth to which weathering processes have a significant influence on creating fractures and exploiting preexisting fractures.

The outer surface of weathered bank faces that are composed of till and Sentinel Butte mudstone and lignite are covered with closely spaced desiccation cracks oriented perpendicular to the bank. Fookes and Denness (1969) reported that bank-perpendicular desiccation cracks began to form in till and mudstone banks within hours on new exposures, but these cracks rarely extended more than about 30 cm into the bank.

Bank Failure Mechanisms

General

Bank recession at Lake Sakakawea and other reservoirs results from a combination of many erosional processes including bank failure, wave erosion, rain splash, runoff, and freeze-thaw cycles. Failure of unstable banks, the most significant erosional process (Millsop, 1985; Reid, 1984; and Doe 1980), occurs when the shear or tensile stress applied to a bank is greater than the strength of the bank material.

There are a variety of bank-failure mechanisms classified according to type of material and type of movement involved (Hansen, 1984; Varnes, 1978). Millsop (1985) observed that most bank recession at Lake Sakakawea results from mass movements of large blocks of bank material as slides, falls, and topples along high-angle fracture planes. He also concluded that the direct results of other active erosional processes, such as wave and frost action, are relatively minor. These forces do, however, play a major role in the oversteepening and weakening of banks, thus indirectly causing eventual failure.

During the most recent stage of this study (1988-1990), despite very low lake levels, banks at Lake Sakakawea continued to recede. Banks at all of the erosion stations are still oversteepened, and at most stations there is evidence of recent large-scale failures along vertical bank-parallel tension fractures (Fig. 31). There is no evidence, however, of slumping or failure along low-angle or oblique surfaces. Erosion from freeze-thaw cycles and associated earth flows and from overland flow is still occurring, but the presence of blocks of material that have broken away from banks and the continued development of large vertical bank-parallel fractures suggests that most of the erosion is still the result of high-angle slides, topples, and falls.

High-Angle Toppling and Sliding Mechanisms

Goodman and Bray (1976) and Evans (1981) have discussed mechanisms associated with toppling, rocks falls and high-angle sliding. Some of these mechanisms are also responsible for bank failures at Lake Sakakawea (Fig. 32). Conditions that promote development of such failures include: high steep banks composed of cohesive material, rapid lateral unloading, the presence of open or weak near-vertical fracture sets oriented subparallel to an exposure face, near-horizonal or oblique fractures dipping out of the bank face, and undercutting by weathering of relatively soft material underlying fractured bank material (Woodward, 1988; Edil and Vallejo, 1980).

Many of these conditions exist for Lake Sakakawea banks. These banks are composed of fine-grained cohesive sediments that contain uniformly oriented vertical fracture sets, and have been subjected to undercutting and rapid lateral unloading. Upper Snow School and Upper Horseshoe Valley till banks, which contain large vertical fractures, and the Sentinel Butte Formation mudstone, which contains relatively weak horizontal and vertical fractures, are especially susceptible to failure by toppling and and high-angle slides along large vertical bank-parallel

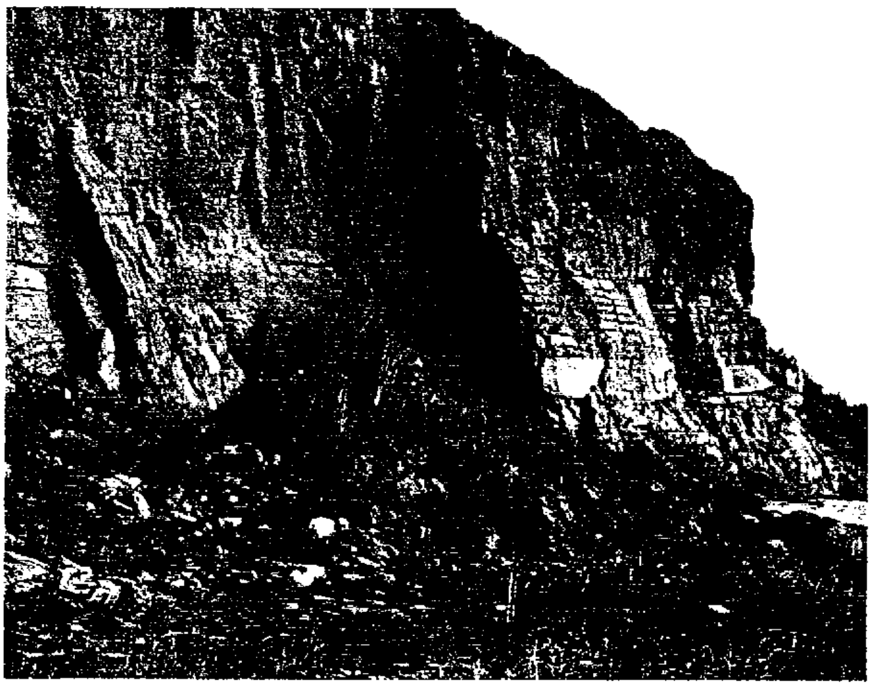


Figure 31. Failure Along Large Vertical Bank-Parallel Tension Fractures in Upper Snow School Till and Underlying Sentinel Butte Formation; Fort Stevenson State Park.

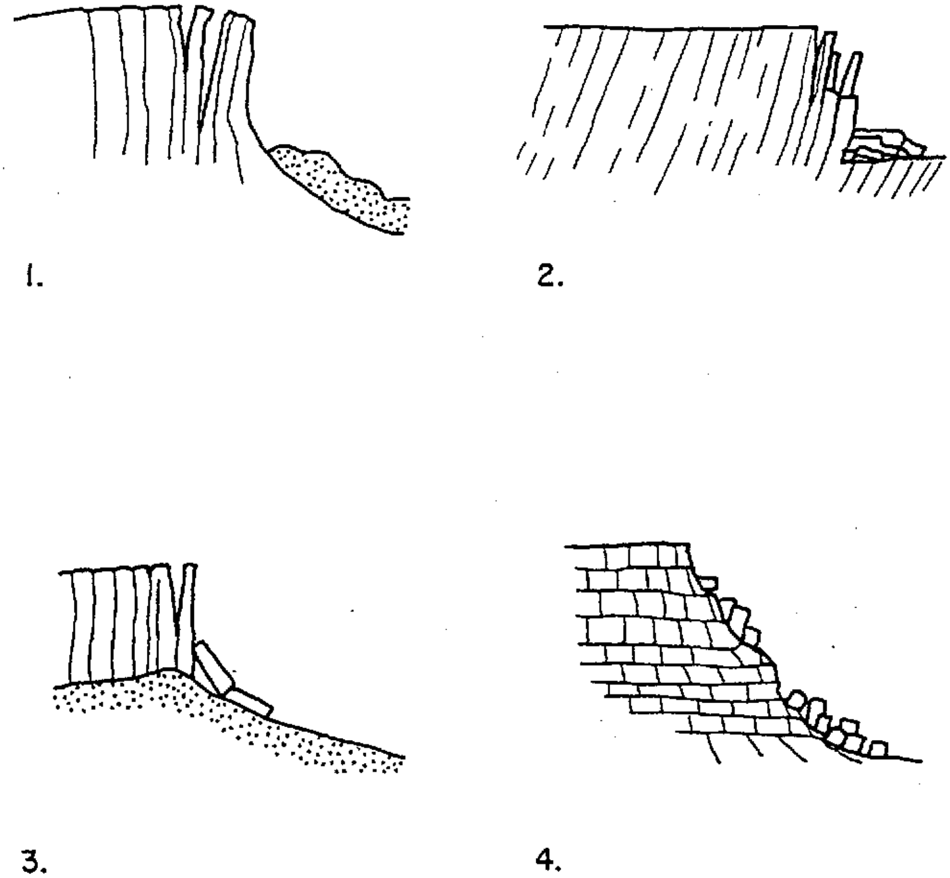


Figure 32. Toppling Mechanisms (after Evans, 1981). (1 = Tension- crack toppling where new vertical fractures form parallel to a steep bank face after lateral unloading. 2 = Flexural toppling; failure occurs along pre-existing, near-vertical, bank-parallel fractures. 3 = Tension fracturing and toppling of fractured material after weathering of relatively weak underlying material).

fractures. These types of failures are not occurring as readily in Upper Medicine Hill till which contains relatively short and strong fractures that are sealed with mineral deposits.

Bank-Parallel Tension Cracks: Most bank failure at Lake Sakakawea is occurring along large bank-parallel tension cracks which extend from the bank top downward. This type failure involves sliding or toppling of large slabs of bank material which break away from or slide along these cracks. These fractures form parallel to the bank face as stress normal to the bank is relieved during erosion. Because of the lack of horizontal discontinuities to disrupt vertical propagation of these cracks, they are especially well-developed in the Upper Snow School and Upper Horseshoe Valley tills, and most erosion at these sites is the result of failure along these cracks.

Block Falls and Topples: Because of the blocky fracture pattern, block toppling and block falls are common modes of failure in banks composed of Sentinel Butte Formation mudstone. Near the bank surface horizontal and vertical discontinuities are weakened by chemical alteration of clay and from physical weathering related to wetting and drying and freezing and thawing. The result of these processes is a bank face with loose blocks of mudstone bounded by weak or open horizontal and vertical fractures. Subsequent failure due to block falls and toppling readily occurs during and after banks are undercut by wave erosion. This type of failure occurs in the Sentinel Butte mudstone in conjunction with failure along large bank-parallel vertical tension cracks that also form in these banks, although not as readily as in the Upper Snow School and Upper Horseshoe Valley tills.

Bank Undercutting: Instability related to undermining of relatively weak or erodible material that underlies vertically-fractured till units may also be contributing to the development of high-angle slides and topples at several sites. At station 51 the Upper Horse Valley till, which has a strong columnar jointing pattern and also contains large bank-parallel tension cracks, overlies an approximately 50 cm thick layer of loose sand and gravel. Undercutting along this sand unit has contributed to instability in the overlying Upper Horseshoe Valley till at this site. This site has both the largest and the most numerous bank-top tension cracks of all the stations (Table 7).

Toppling along large bank-parallel tension cracks at stations 55 and 56, which have experienced the most rapid bank recession, probably is promoted by instability of the underlying clay-rich Sentinel Butte Formation. At these stations the banks are composed of columnar-jointed Upper Snow School till and underlying Sentinel Butte mudstone which is particularly clay-rich in this area. Instability of the mudstone due to weathering processes might lead to differential settling and subsequent failure along fractures in the overlying till formation, as suggested by the unusually large recession rates at these sites. Tests of variations in bearing capacity at different depths into the weathered bank surface are needed to verify the likelihood of this process, however.

Fractures and Bank Recession

General

During this study much was learned about factors controlling variations in fracture patterns at different sites and in different lithologies, and much was also learned about how these fracture patterns affect bank stability. Nevertheless, fracture characteristics are just a part of the large number of interrelated factors affecting bank erosion rates, including lake levels, waves and wind, microclimate, bank and beach geometry, and inherent bank strength; thus, it is still difficult to correlate fracture patterns to differences in bank erosion rates.

For example, one geologic factor that shows a strong correlation with low lake level erosion rates is bank height. Overall bank recession since 1983 is independent of bank height (Fig. 33a), but Figure 33b indicates that most of the recession for low banks occurred during high lake levels, whereas most erosion for high banks occurred during low lake levels. Therefore, if water levels remain low high banks will probably continue to erode longer and eventually farther back.

Fracture Orientations

Banks oriented subparallel to consistent vertical fracture sets fail more easily, and therefore are expected to recede faster. Figure 34 shows the difference between bank orientation and the orientation of the nearest consistent vertical fracture set for stations with banks composed of Upper Snow School and Upper Horseshoe Valley till plotted against total bank recession. This graph reveals no obvious correlation, suggesting that orientations of consistent vertical fracture sets with respect to bank orientation is not a dominant factor controlling variations in recession rates for these tills.

The orientation of vertical fractures sets do not correlate with differences in erosion rates in other units either (Appendix II). For example, bank erosion rates are similar for each of the three stations with Upper Medicine Hill till banks and are largely controlled by variations in lithology at stations consisting of Sentinel Butte Formation banks.

Even though there is not a significant correlation seen between bank erosion rates and orientation of fracture sets for all of the sites studied, this is still an important erosional factor at some locations. For example, the highest bank erosion rates were recorded at stations 54, 55, and 56 in Fort Stevenson State Park where banks are composed of Upper

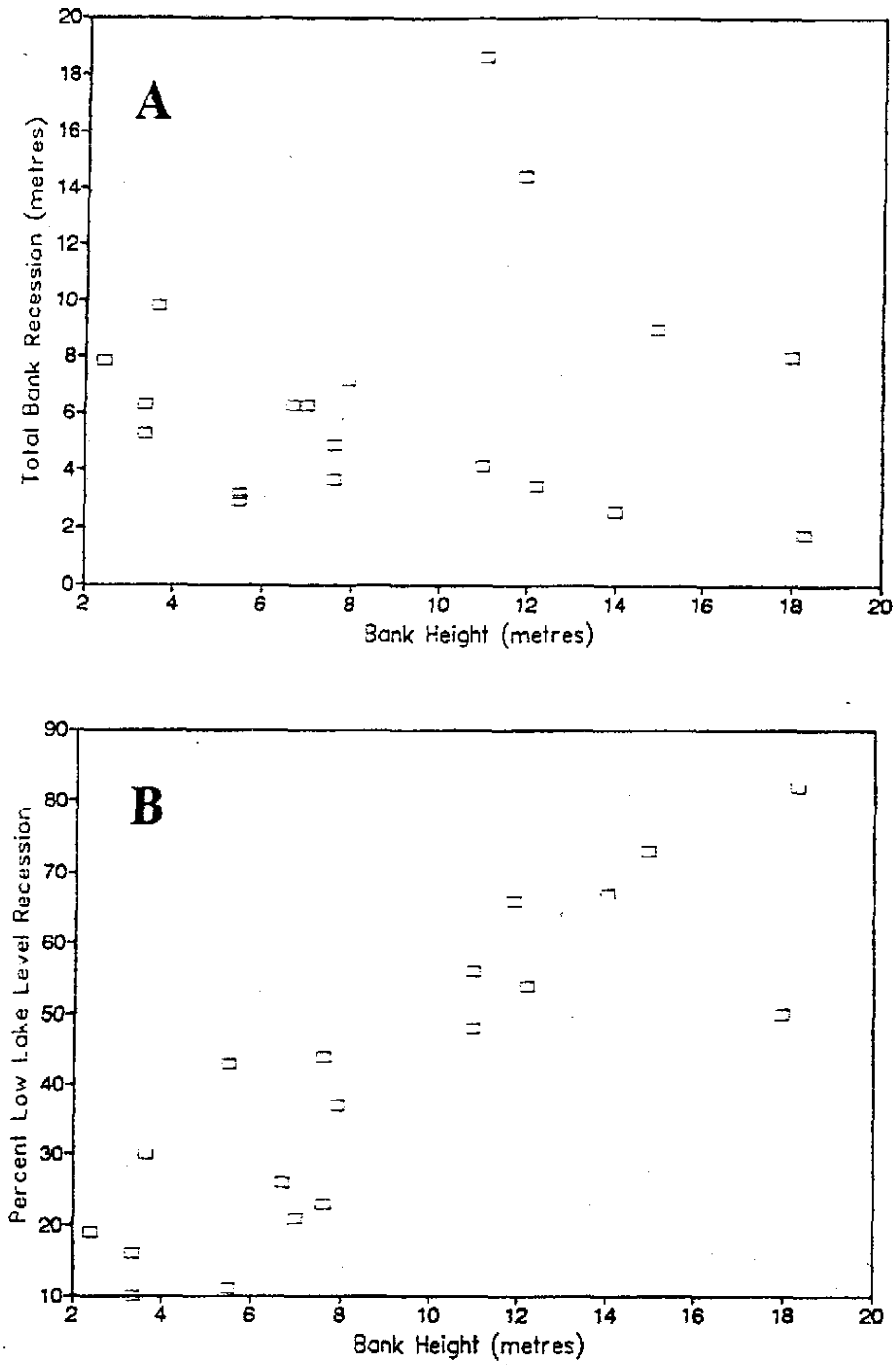


Figure 33. Bank Height and Bank Recession Rates. a. Total bank recession vs. bank height. b. Percent low lake level recession vs. bank Height.

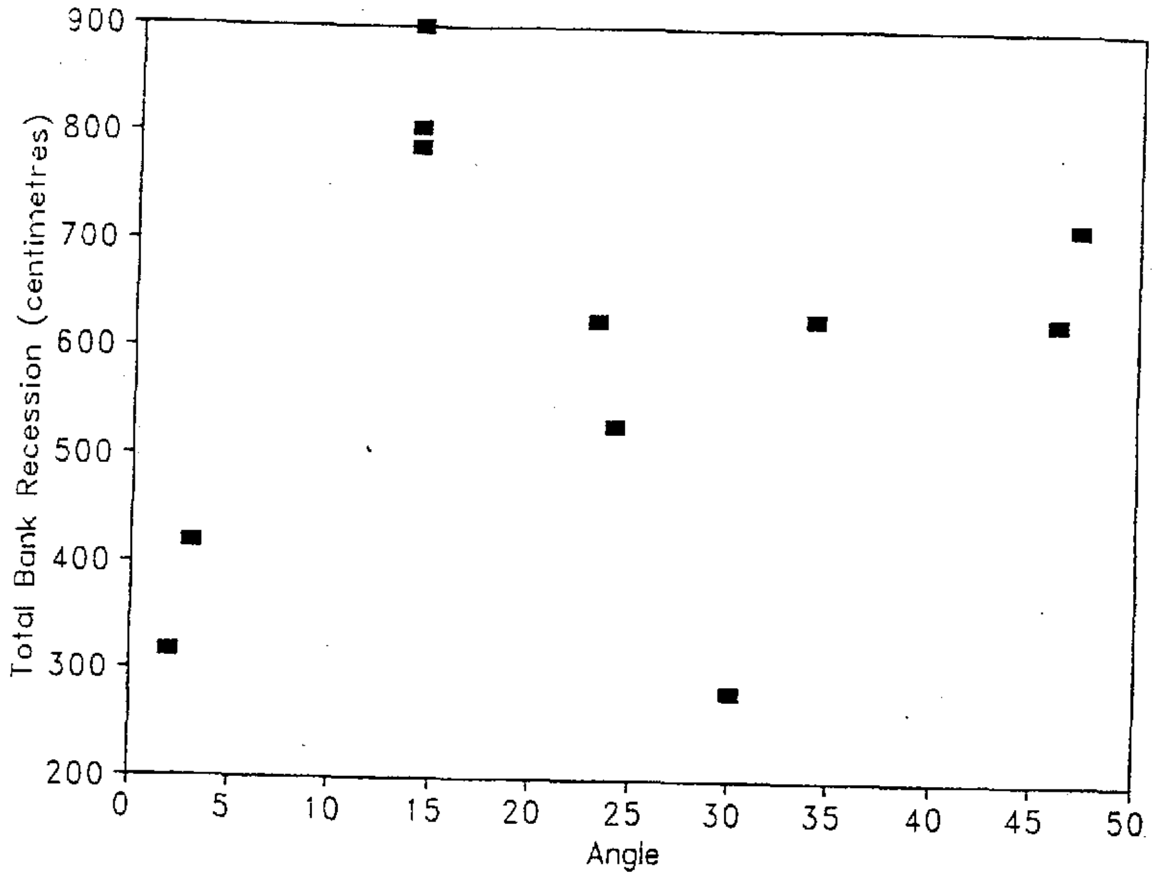


Figure 34. Vertical Fracture Set minus Bank Orientation Angle vs. Total Bank Recession.

Snow School till overlying the Sentinel Butte Formation (Fig. 35). The banks at these sites are nearly parallel to strongly developed NW-SE vertical fracture sets in the Sentinel Butte Formation.

Erosion Rates of Tills

Banks composed of Upper Horseshoe Valley and Upper Snow School tills have receded 5.3 to 9.0 m between 1983 and 1990 while those composed of Upper Medicine Hill till have receded only 2.6 to 3.6 m during the same period (Fig. 35). This difference can be attributed mainly to differences in fracture patterns. The Upper Horseshoe Valley and Upper Snow School tills have more long vertical fractures that serve as vertical failure planes. Due to a lack of horizontal discontinuities in these tills, large tension cracks that initiate along vertical fractures extend the entire depth of the bank in some locations (Fig. 31). Bank-parallel tension fractures are exposed as long surface cracks at the bank tops at all of the stations underlain by these tills (Table 7).

Horizontal fractures are well-developed and more abundant in the Upper Medicine Hill till; thus, vertical fractures are shorter on average and large bank-parallel tension fractures do not develop as well. Also, fractures in the Upper Medicine Hill till are stronger, so failure is less likely to occur along them. Although the strength along these fractures has not been tested, nearly all of the Upper Medicine Hill till fractures are sealed with mineral coatings, whereas many of the vertical fractures in the other tills are visibly open (Appendix III).

There are other factors besides fractures that might be affecting the differences in erodibility of these tills. The density of the Upper Medicine Hill till is considerably higher than that of the Upper Horseshoe Valley till and on average is slightly higher than the density of the Upper Snow School till (Millsop, 1985). Because of this the Upper Medicine Hill till might be more resistant to weathering, wave erosion, and the development of bank-parallel tension fractures. The Upper

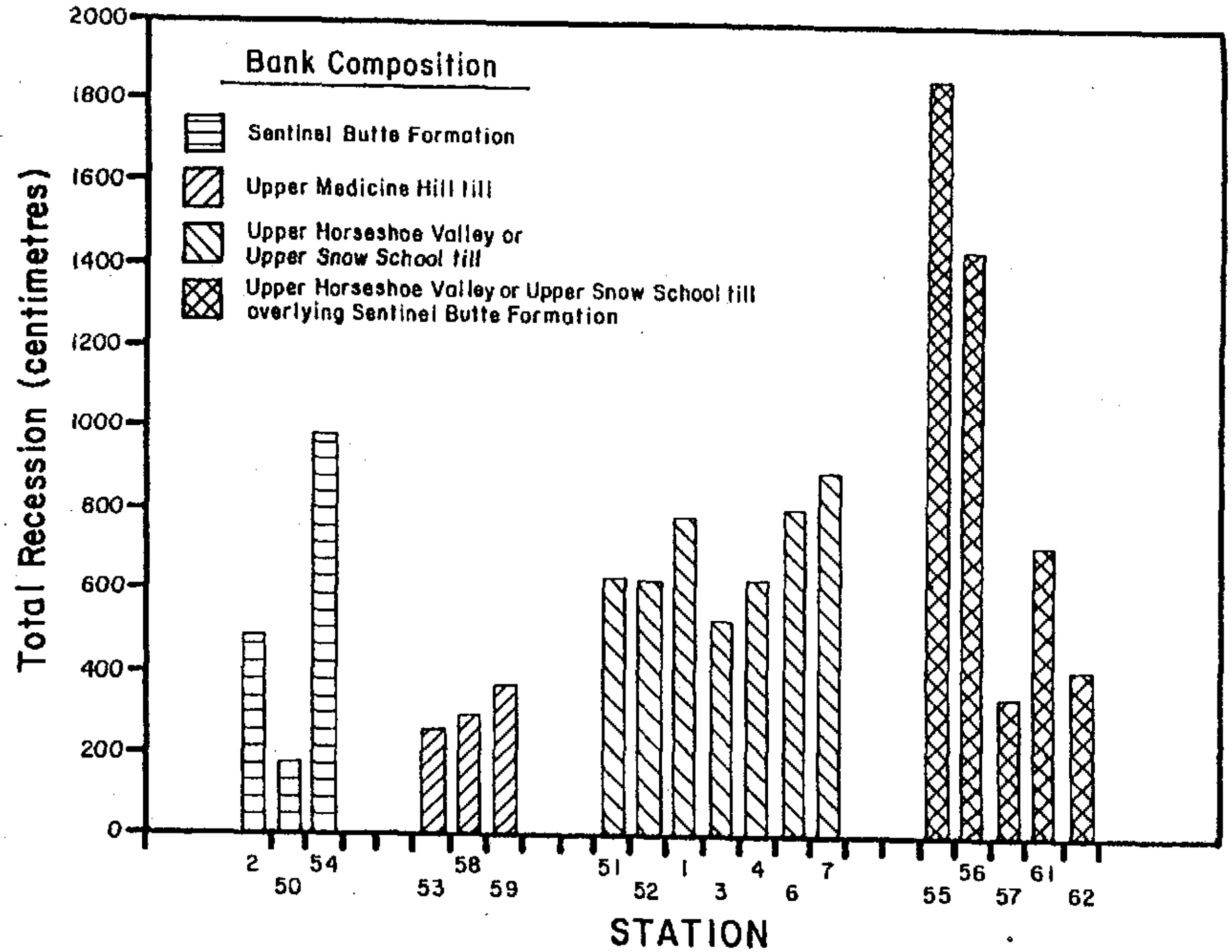


Figure 35. Bank Recession by Station and Lithology (1983-1990).

Medicine Hill till also contains more boulders than the other two tills. Therefore, the beaches at Upper Medicine Hill stations are armored by boulder lag deposits which protect them from wave erosion.

Sentinel Butte Formation

The large variations in bank erosion rates for the three stations composed of the Sentinel Butte Formation (Fig. 35, stations 2, 50, and 54) can be explained by differences in lithology. During this study, the total recession at station 2 of five metres is about average for all of the stations. Station 50, however, has undergone the least amount of erosion (< 2 m), and station 54, which has eroded back nearly ten metres, represents one of the fastest receding banks.

The bank at station 50 is steep and nearly 20m high. Although it appears to be unstable, it has undergone the least erosion of all stations. The Sentinel Butte Formation here consists of interbedded mudstone, lignite, and well-indurated limestone lenses (Fig. 36). The abundant limestone lenses add to the overall strength of this bank and the occurrence of repetitive bedding separating distinct lithologies has prevented the formation of long vertical fractures and bank-parallel tension fractures here. Also, the beach at this site is protected from wave erosion by massive slabs of concretionary limestone that have eroded out of the bank.

Station 54, which has experienced rapid recession, consists of a clay-rich facies of the Sentinel Butte Formation that is highly fractured due to desiccation, indicating its susceptibility to weathering. Most of the recession (70%) at this site occurred during high lake levels when this relatively weak sediment was subjected to wave erosion. In addition, the beach here is not protected by boulder or concretionary riprap as at station 50.

Figure 36. Station 50, Beach and Bank.

Till Overlying the Sentinel Butte Formation

The large variations in recession rates for banks composed of the Upper Horseshoe Valley or Upper Snow School tills overlying the Sentinel Butte Formation (Fig. 35) are more difficult to explain. For these stations, recession was lowest at station 57 (2.8 m) where the underlying Sentinel Butte Formation consists of interbedded channel sand and well-indurated lenses and spherical concretions. Horizontal bedding of distinct lithologies, together with the well-indurated limestone lenses, probably account for the slower erosion rate here.

The unusually large recession rates at stations 55 and 56 remain unexplained (Fig. 35). These sites are near each other in Fort Stevenson State Park and the bank geology is similar at both sites. Bank erosion has been rapid at these sites throughout the project history, during warm and cold seasons, and during high and low lake levels (Table 1). It is uncertain whether these high erosion rates are a net result of many favorable conditions, such as a large fetch, an unprotected beach, high steep banks, and sympathetically oriented vertical fracture sets, or if these high rates can be attributed partly to some other factor that has not yet been recognized. One possibility is differential settling of vertically fractured and relatively rigid overlying Upper Snow School till on underlying clay-rich Sentinel Butte Formation mudstone which has become unstable due to weathering.

Current and Future Bank Recession Trends

General

The previous section considered some of the factors that influence site-specific variations in sort-term bank recession rates, especially the effects of fractures. This section is a discussion of trends in average bank recession rates observed from 1983 through 1990 which have been strongly influenced by lake level fluctuations. Speculation regarding future bank recession rates is also included.

Lake Level Fluctuations

Seasonal observations of Lake Sakakawea bank recession rates during the last eight years show that rapid bank erosion (averaging over 2.0 m/yr) occurs when lake levels reach or exceed an elevation of 562 m above sea level, the "critical level", for an extended time. During low lake levels, erosion continues but at much slower rate (averaging less than 0.5m/yr) (Fig. 7). Thus, knowledge of the magnitude and duration of water level fluctuations is essential to predicting rates of erosion. The reason for this relationship is that during high lake levels wind-driven waves are able to erode the base of shoreline banks directly, causing oversteepening and relatively rapid large-scale failures. After lake levels fall, the oversteepened banks continue to fail, but at a slower rate, until an equilibrium profile is achieved. Similar correlations between lake levels and bank erosion rates have been documented during studies on the Great Lakes (Larson, 1973; Mickelson and others, 1977).

In light of the above relationship, several important questions remain to be answered:

-How often will high lake levels be reached in the future?

-What will the magnitude and duration these conditions be?

-How long and how far will bank recession proceed if lake levels remain low?

Unlike natural lakes, the level of Lake Sakakawea is not controlled primarily by regional weather patterns. Instead, the level is controlled by the U.S. Army Corps of Engineers (Corps) which regulates the amount of water flowing through the Garrison Dam. Their decisions are based on conditions affecting the entire Missouri and Mississippi River drainage basins, with little regard to local concerns; thus, attempting to predict future lake level fluctuations is difficult. According to Corps records (Garrison Dam Operations Monthly Reports), lake levels have exceeded the "critical level" for periods ranging from three to six months five times in the last 12 years (1979-1991). If this is representative of subsequent fluctuations, bank erosion may continue indefinitely at about the same rate as it has during the eight years of this study.

The Corps originally assumed that even under constant high lake levels shoreline banks would eventually reach a quasi-stable condition, thus limiting total bank recession (Cordero, 1982). This assumption was based on the template theory which assumes that the material eroded from these banks would be deposited and conserved in the foreshore and immediate offshore zones, allowing stable shelves to build up, protecting banks from continued wave erosion, and allowing them to backwaste to a stable angle.

This template theory is not valid for Lake Sakakawea, however. The till and mudstone banks along this lake are composed primarily of clay and silt-size particles that are readily transported away from the nearshore zone. Steep drop-offs exist parallel to most of the shorelines and waves and associated currents easily carry this fine-grained material to deep water where it settles out. Also, sediment eroded from headlands by longshore current is transported into the many deep bays found along the shorelines of this lake. These bays act as sediment traps, resulting in sediment starvation of headland beaches.

Because of these processes, erosion of Lake Sakakawea shorelines could continue indefinitely or at least until headlands are eroded and bays are filled in. Historical studies on the Great Lakes indicate that bank erosion has been occurring there at rates of 0.4 to over 3.0 m/yr for at least 150 years (Quigley and others, 1977; Buckler and Winters, 1983). Erosion rates of these shorelines are also higher during periods of high lake levels when direct wave action is a factor. Then, following high lake levels, erosion continues due to bank instability but at slower rate (Larson, 1973; Quigley and others, 1977).

Lake levels at Lake Sakakawea have been too low the last four years (1987-1990) for direct wave erosion of banks to occur. Nevertheless, these banks, still unstable from wave erosion in 1986, have continued to recede at a relatively slow rate. One might expect that these banks eventually will erode to a stable profile if water levels remain low; but, even if water levels do remain low, they may still experience continued wave erosion in the future. After testing underwater erosion measuring techniques, Robin and Davidson-Arnott (1986) reported that till underlying offshore and foreshore wave zones erodes more than enough to keep up with receding banks, and Kamphuis and Asce (1987) demonstrated that where abrasive sediment was available, recession rates of glacial bluffs along Lake Erie were controlled more by foreshore erosion rates than by lake level fluctuations.

Although the water level along Lake Sakakawea is presently far from the wave-cut banks, small erosional scarps are forming in the primary beach material at the wave breaking zone in many places. This is an indication that wide beaches now separating banks from the water edge could eventually erode down far enough to allow the lower water levels to once again reach shoreline banks. The rate of this beach erosion has not been determined, but most beaches are presently 50 to 75 metres wide and the lake level is currently about 6 metres below normal. Therefore, the most erodible beaches would probably take at least 10 years to recede to the base of their existing banks. Beaches veneered with large boulders eroded from the Upper Medicine Hill till or with concretionary lenses from the Sentinel Butte Formation would erode back at a slower rate. Records of past lake level fluctuations, however, suggest that water levels will rise again before beach levels are eroded down to the current water levels.

Bank Recession Prediction

The U.S. Army Corps of Engineers initiated this project in 1983 to study bank recession rates, erosion processes, and controlling factors. It was also hoped that a model for predicting site-specific bank recession rates could be developed to aid in land-use planning and the selling and purchasing of lake-side real estate. Since then, bank recession rates have been monitored at least yearly and several equations based on regression analyses were developed to predict site-specific bank recession rates (Reid and others, 1988; Sandberg, 1986).

Assuming that recession rates similar to what we have measured during the past eight years continue into the future, the ability to predict site-specific erosion will be an important part of area land-use management. At the present, average yearly bank recession rates determined during this eight-year study for areas exposed to wave erosion range from 0.25 to 2.65 m/year. The design operating life of this reservoir is approximately 500 years (Sandberg, 1986, p. 108); therefore, if bank erosion continues at its current rate, the maximum recession that will occur during the life of this reservoir is approximately 1.3 kilometres (0.8 miles).

The areas of most concern are rapidly receding headlands and other shorelines exposed to wave erosion. Erosion of inlet shorelines is relatively minor, and it is assumed that these bays will fill in with sediment, perhaps eventually resulting in progradation of shorelines in these areas. Many of the headlands at the eastern end of Lake Sakakawea are one to two kilometres long (Fig. 2); therefore, it is possible that these will continue to recede throughout the entire life of the reservoir with ultimate recession of as much as one kilometre.

Some of the approaches used to predict shoreline bank recession are: slope stability analyses, which are based on current physical characteristics of a bank (Edil and Vallejo, 1980), statistical analyses, where observed bank recession rates are correlated to site-specific factors associated with bank erosion (Sandberg, 1986; Spoeri and others, 1985; Gatto and Doe, 1983), and other studies that have dealt with historical trends over large tracts of shoreline (Buckler and Winters, 1983; Quigley and others, 1977; and Larson, 1973).

Slope Stability Analyses: Slope stability analyses are used to assess the stability of natural slopes and to design stable excavated slopes at a minimum cost. Attempts have also been made to use stability analyses to predict variations in shoreline erosion rates (Edil and Vallejo, 1980). They are based on the physical properties of the bank, including strength and density, and elements of the bank geometry (height and the slope angle).

Traditional stability analyses involve the estimation of shear stress due to gravitational forces along the most probable failure surfaces and comparing it to the strength of the soil. Because the distribution of stresses in a bank varies with distance from the slope face and bank top, most procedures assume that failure will occur along a curved surface dipping between 30° and 50° (Das, 1985, p. 442). These methods are intended to test the stability of slopes that are near the threshold of slumping along rotational slip planes and do not apply to the banks at Lake Sakakawea which are steep and actively eroding along high-angle failure planes.

Slope stability analyses still might be useful in assessing variations in short-term recession rates. At Lake Sakakawea these analyses must assume that vertical fracture planes are the most probable failure surfaces and that failure will occur by toppling and high-angle sliding after fracture surfaces are weakened by tensional forces and weathering. The strength of these banks is, therefore, dependent on the frequency, size, and orientation of vertical fractures and on the strength along their surfaces. Due to this study, more is known about variations these fracture properties, but strength parameters along fracture planes for different lithologies must be determined, and the effects of weathering on these strength parameters must also be assessed. Even with these considerations, predicting erosion rates at Lake Sakakawea by this means will be difficult.

Woodward (1988) concluded that a procedure he developed for predicting the likelihood of toppling along vertical fracture planes was limited because other factors, such as lateral stress relief, undercutting, and changes in fracture strength due to weathering, compromise the validity of any equation that does not take into account changes in strength and bank geometry over time. A similar problem was encountered in designing safe slopes in the fractured Harlford till (McGown and others, 1974). Tests indicated that this till would most likely fail along vertical fractures that had a design strength of about 60kN/m^2. After the slopes were completed, however, numerous small-scale failures occurred along fracture surfaces weakened by weathering.

Edil and Vallejo (1980) had difficulties in attempting to use slope stability models to predict bank recession on the Great Lakes. Their models were somewhat successful for short-term predictions under controlled conditions; however, dynamic shoreline conditions continually caused changes in bank geometry and strength parameters of near-surface bank material.

At Lake Sakakawea more engineering data are also needed before meaningful slope stability analyses can be conducted. For example, the Corps (1981, p. 27-28) reported the design shear strength for the glacial tills in the area as having the following average parameters: cohesion equal to 29 kN/m2 and an internal angle of friction equal to 20°. Dry densities of the tills range from 12 to 17 kN/m3, the moisture content ranges from 11 to 34%, cohesion ranges from 4.8 to 144 kN/m2, and the internal angle of friction ranges from 8 to 34°. These wide-ranging values reflect the heterogeneity of the tills and the need for more accurate site-specific testing of engineering properties. Large lithologic variations in the Sentinel Butte Formation merit more detailed site-specific testing for this geologic unit also.

Slope stability analyses take into account only the internal physical properties of the bank; thus, this type of procedure alone cannot be used to explain all slope stability differences and variations in bank recession rates at Lake Sakakawea where external forces, such as wave action, climate, topography, lake level changes, vegetation, and the affects of weathering, also play a major role in bank failure processes and rates. Because it is difficult to assess the effects of these factors and processes quantitatively, statistical procedures have been the favored approach to predicting shoreline recession.

__Regression Analyses:__ Regression analyses used to correlate bank recession rates with erosional factors were attempted at Lake Sakakawea. (Gatto and Doe, 1983; Millsop, 1985; Sandberg, 1986; Elliott and Reid, 1989). Millsop, and Gatto and Doe, were unable to generate statistically significant models; however, Millsop's (1985) analyses showed that variables most closely associated with bank recession, listed in order of importance, were lake levels, wind speeds, and wind directions. Because of high lake levels during Millsop's study (1983-1984), these factors were all related to wave erosion.

Sandberg (1986) used regression analyses to develop separate equations for predicting warm- and cold-season bank recession rates. The warm-season equation was based on the following independent variables: offshore slope, beach width, bank orientation with respect to the dominant wind direction, and bank height; the independent variables for the cold-season equation were bank height and bank orientation with respect to the sun. Both of these equations were statistically significant in that the probability that the independent variables were explaining random dependent variables was < 5% for the warm-season equation and < 1% for the cold-season equation; however, the ability of these equations to explain the variations in the dependent variable was too low to predict site-specific bank recession accurately.

Similar results were obtained in subsequent attempts to use these types of equations for predicting high and low lake level recession rates (Elliott and Reid, 1989). The independent variables used in these analyses for the high lake level periods were: effective fetch, percentage of beach clasts greater than cobble-size, bank height, and beach composition; and independent variables for the low lake level equation were: bank height and bank orientation with respect to sun. These analyses were also based on two additional years of bank recession measurements which were used to determine the dependent variables (bank recession rates).

This type of statistical approach might be more successful in the future when variables such as lithology, fracture patterns, strength parameters, and susceptibility to weathering are considered. Although no single fracture characteristic by itself can be directly correlated to variations in bank erosion rates, the present study has demonstrated that these factors do influence bank failure mechanisms and bank erosion rates and must be incorporated into statistical models or slope stability models used to predict variations in recession rates.

If the most important variables could be isolated, statistical approaches such as mentioned here are probably still unreliable in the short term. This is because of the numerous random variables that cannot be incorporated into such equations, including the occurrence of storms during relatively short high lake levels, heavy rainfall, or variations in the magnitude of cycles related to weathering. Also, erosion due to bank failure results in sporadic erosion rates that must be monitored over long periods to determine a representative rate. This problem is illustrated by the yearly recession for station 58 where it is apparent that continued bank recession monitoring is needed before representative rates are available (Fig. 37).

Slope stability and statistical models for predicting bank erosion might be useful in the future after more data are collected, but at the present, where determining accurate erosion rates is critical, such as at state parks, reliable data still must be obtained from direct measurements of bank erosion. Directly measuring bank erosion rates along the entire shoreline of the lake would be a monumental task, and this is not recommended. However, where predicting magnitudes of future bank recession rates is critical, erosion rates should be monitored using techniques similar to those employed for this project. This procedure is very simple and inexpensive. At other sites it is recommended that estimates of future short-term bank erosion rates be based on the maximum recession rate determined during this study and from Corps' sediment rangeline surveys for banks with similar geology. For example, banks composed of mainly Upper Horseshoe Valley and Upper Snow School tills have receded at fairly constant rates, ranging form 0.75 to 1.3 m/year during this study (Fig. 35), while erosion rates of banks composed of the Upper Medicine Hill till have ranged from about 0.35 to 0.50 m/year. Erosion of banks composed primarily of Sentinel Butte Formation mudstone vary considerably, however. These rates ranged from about 0.60 to over 2.5 m/year.

Recommendations for Further Studies

This thesis is part of an ongoing project, begun in 1983, to study bank recession on Lake Sakakawea. The ultimate goal is to learn enough about bank erosion processes and factors so that eventually variations in site-specific erosion rates and ultimate bank recession can be predicted

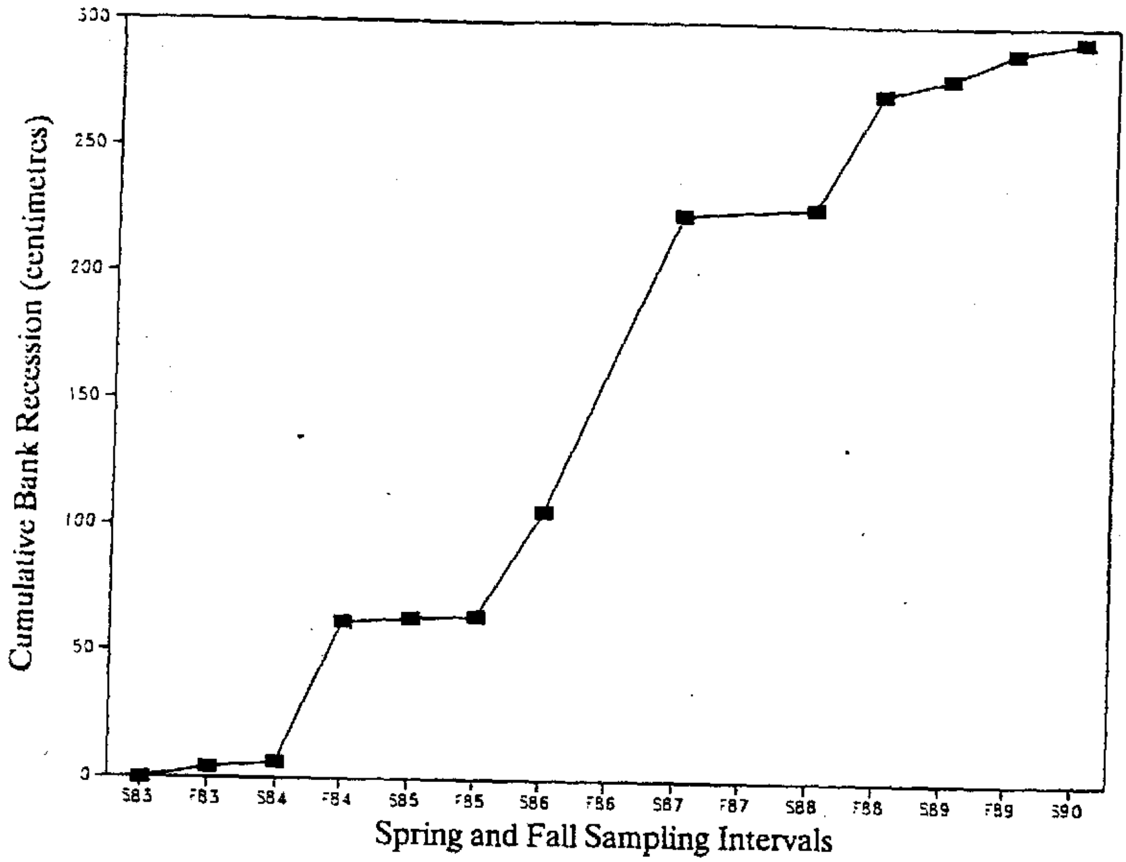


Figure 37. Cumulative Bank Recession, Station 58, Spring 1983 to Spring 1990.

accurately. During the first eight years of this study much has been learned about recession rates and the associated erosional processes, but continued work is needed to achieve the goals of this project.

Continued monitoring of established bank recession stations will improve the accuracy of estimated site-specific and average erosion rates. Bank erosion events at Lake Sakakawea occur sporadically, especially during low lake levels; thus longer periods of monitoring will improve the accuracy of bank recession rate data.

Bank erosion stations are inexpensive and easy to establish and monitor. Increasing the number of stations would yield more information on variations in site-specific erosion rates. The Corps' sediment rangelines, along which surveys of bank positions and lake profiles are made periodically, can also be a valuable source of bank recession data if they are conducted at a higher level of accuracy in the future. Determining site-specific variations in rates of beach erosion might also be important in the future. This will be especially important if lake levels remain low for long periods. Under these conditions, sites with more erodible beaches will be vulnerable to beach downcutting followed by direct bank-toe wave erosion.

More detailed testing of textural, physical, and strength properties of bank-forming lithologies is needed before meaningful slope stability analyses can be used to predict site-specific variations in bank erosion. Determining average strength parameters along fracture surfaces for the major lithologies represented will be important if these analyses are to be used. The reliability of statistical bank recession models based on regression analyses could also be improved if more accurate and detailed data pertaining to these properties are incorporated.

Determining how much total sediment eroded from shoreline banks is being deposited in the lake, where it is being deposited, and at what rates, would also be helpful in predicting long-term erosion rates and maximum recession. This type of information could be obtained from cores of lake bottom sediments.

CONCLUSIONS

Fractures

- Variations in bank fractures characteristics such as length, frequency, and orientations of sets correspond to changes in lithology.
- The Sentinel Butte Formation bedrock typically consists of bedded mudstone with a blocky fracture pattern composed of well-developed straight vertical fractures intersecting and cutting across horizontal fractures and bedding planes. Most vertical fractures belong to one of four persistent sets; average azimuths are 5°, 45°, 95°, and 140°. Sandstone facies have long widely spaced vertical fractures and few horizontal fractures. In lignite and adjacent clays vertical and horizontal fractures are small, well-developed, and very closely spaced.
- Upper Medicine Hill till vertical fractures are short and closely spaced. Most terminate at intersections with well-developed oblique and horizontal fractures. At the sites studied there are two to four vertical fracture sets; their orientations do not change between sites. Nearly all of these fractures are closed or sealed with mineral coatings.
- The Upper Horseshoe Valley and Upper Snow School tills contain few horizontal fractures and vertical fractures are straight, long, and widely spaced. Most Upper Horseshoe Valley till vertical fractures belong to well-defined NW-SE or NE-SW orthogonal sets. Upper Snow School till fractures are shorter on average, more directionally dispersed, and orientations of sets do not correspond between sites.
- Orthogonal vertical sets in the Sentinel Butte Formation and the Upper Horseshoe Valley till are likely the result of crustal stresses related to uplift and maximum NE-SW horizontal compression. Horizontal fractures in the Sentinel Butte Formation and the Upper Medicine Hill till

were likely caused by stress release during deglaciation. The greater variation in fracture types and directions in the Upper Medicine Hill and Upper Snow School tills suggests other processes, such as dewatering upon deglaciation, stress release, weathering, and possibly subglacial deformation had a greater influence on these sediments.

► Vertical fracture lengths and frequency are controlled mainly by abundance and development of horizontal discontinuities and less so by factors such as grain size and degree of consolidation. Longer and more widely spaced fractures exist where horizontal structures are absent or poorly developed, and where horizontal structures are well-developed and frequent, vertical fractures are closely spaced and shorter. Fracture frequencies increase near the top few metres of banks due to weathering processes. Desiccation fracturing is especially intense in clay-rich material.

► The most common erosional mechanism of Lake Sakakawea banks is failure due to toppling and sliding along high-angle fracture planes after banks are weakened and oversteepened by wave action, stress release and weathering. Banks without abundant horizontal structures and which contain vertical bank-parallel fracture sets (Upper Horseshoe Valley and Upper Snow School tills) are especially susceptible to this type of failure. Erosion of Upper Medicine Hill till banks, where short vertical fractures intersect horizontal fractures and which are closed or sealed with mineral coatings, have eroded about 50% slower. Erosion of Sentinel Butte Formation banks, with strong vertical lithological variations or abundant hard concretionary lenses, has been slower also.

Bank Erosion Trends

- Rapid bank erosion (>2.0 m/year), resulting from direct wave action, occurs when lake levels reach an elevation 562 metres. During lower lake levels bank recession has continued at a slower rate (0.2m/year).
- If lake level fluctuations continue as they have in the past, erosion rates will likely remain similar to current rates throughout the reservoir life. If lake levels remain low, recession rates will decrease as banks become more stable; however, many beaches will then erode down, adjusting to the lower water level, allowing wave erosion to continue.
- Statistical models, used for predicting site-specific recession rates have not been accurate; however, continued monitoring of established erosion stations and additional stations, along with incorporating more data on variations in bank lithology and bank structures, will help to improve these models.
- Currently, the most effective means of predicting bank erosion is using erosion rates measured during this project and from Corps' sediment rangeline surveys to estimate maximum rates for banks with similar characteristics. Where determining accurate bank erosion rates is critical, stations similar to those used for this project should be established. This procedure is inexpensive and continued monitoring requires only minor involvement of time.

APPENDIX I

BANK RECESSION STATION HISTORY

EXPLANATION

Recession-	Sum of decreases in distance from all of the measuring pins at a station between measurements.
Accumulation-	Negative sum of increases in distance from all of the measuring pins at a station between measurements.
Pins-	Number of measurement and alignment pin pairs at the station indicated.
Average Recession-	Sum of recession and accumulation divided by the number of pins for a given station. Calculated for each measurement interval.
Negative Numbers-	Negative numbers indicate a temporary net expansion of a bank due to soil swelling or opening of bank-parallel tension fractures.

STATION 1

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	14	40	16	-3	-2	
2	7/13/83	92	9	15	6	4	
3	8/22/83	774	3	14	55	59	
4	10/16/83	218	18	14	14	73	
5	5/10/84	5	58	14	-4	69	70
6	5/30/84	65	16	14	4	73	
7	7/12/84	2350	0	14	168	241	
8	7/23/84	474	0	7	68	309	
9	8/23/84	630	0	14	45	354	
10	9/23/84	99	0	14	7	361	
11	10/13/84	29	0	14	2	363	
12	3/11/85	5	38	12	-3	360	
13	4/28/85	9	18	14	-1	359	290
14	6/20/85	737	1	15	49	408	
15	8/3/85	144	3	15	9	417	
16	8/31/85	4	7	8	0	417	
17	6/28/86	137	10	8	16	433	74
18	7/16/87	2782	0	8	348	781	348
19	4/30/88	38	18	8	3	784	3
20	6/27/88	4	15	8	-1	783	
21	8/16/88	20	1	7	3	786	
22	10/8/88	8	10	8	0	786	
23	5/10/89	15	8	8	1	787	2
24	8/11/89	11	55	8	-6	781	
25	10/13/89	53	12	8	5	786	
26	5/17/90	37	22	8	2	788	2

* negative numbers indicate a net expansion of the bank toward the lake since the previous measurement

STATION 2

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	0	5	0	--	--	
2	7/13/83	0	1	3	0	0	
3	7/28/83	8	6	8	0	0	
4	8/22/83	125	18	8	13	13	
5	10/16/83	14	13	8	0	13	
6	5/9/84	12	4	8	1	14	14
7	5/30/84	28	0	8	4	18	
8	7/12/84	277	10	8	33	51	
9	7/23/84	120	0	8	15	66	
10	8/23/84	1002	1	8	125	191	
11	9/13/84	0	10	8	-1	190	
12	10/14/84	--	--	--		190	
13	3/11/85	382	11	8	46	236	
14	4/28/85	61	171	8	-14	222	208
15	6/20/85	184	2	10	18	240	
16	8/30/85	2	29	10	-3	237	
17	8/31/85	186	11	9	19	256	
18	6/28/86	360	20	9	38	294	73
19	7/16/87	1239	0	8	155	449	155
20	4/30/88	44	26	8	2	451	2.2
21	6/27/88	19	20	8	0	451	
22	10/8/88	11	29	8	-2	449	
23	5/10/89	215	4	8	26	475	24
24	8/10/89	179	84	8	12	487	
25	10/13/89	36	16	8	3	490	
26	5/17/90	6	29	8	-3	487	12

STATION 3

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	10	5	6	1	1	
2	7/13/83	8	12	6	-1	0	
3	8/22/83	21	0	6	4	4	
4	10/10/83	1	6	6	-1	3	
5	5/9/84	4	8	6	-1	2	2
6	5/30/84	9	0	6	2	4	
7	7/12/84	365	0	6	61	65	
8	7/23/84	747	0	6	125	190	
9	8/23/84	335	0	6	56	246	
10	9/13/84	514	0	6	86	332	
11	10/13/84	1	0	5	0	332	
12	3/11/85	22	1	6	4	336	
13	4/28/85	90	2	6	15	351	349
14	6/20/85	72	2	8	9	360	
15	8/3/85	33	2	8	4	364	
16	8/31/85	116	2	8	14	378	
17	6/28/86	136	12	7	18	396	45
18	7/16/87	1048	0	8	131	527	131
19	4/30/88	5	56	8	-6	521	-6
20	8/16/88	31	9	7	3	524	
21	10/8/88	12	8	8	1	525	
22	5/10/89	1	31	9	-3	522	1
23	8/14/89	36	2	9	4	526	
24	10/13/89	47	1	9	5	531	
25	5/17/90	19	4	8	2	533	11

STATION 4

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	1	3	4	-1	-1	
2	7/13/83	11	0	4	3	2	
3	7/29/83	2	4	4	-1	1	
4	8/22/83	3	3	4	0	1	
5	10/16/83	1	9	4	-2	-1	
6	5/9/84	50	1	4	12	11	12
7	5/30/84	11	9	4	1	12	
8	7/13/84	285	0	4	71	83	
9	7/23/84	164	0	4	41	124	
10	8/24/84	325	0	4	81	205	
11	9/13/84	11	0	4	3	208	
12	10/13/84	65	0	4	16	224	
13	4/28/85	12	7	4	1	225	214
14	6/20/85	153	0	4	38	263	
15	8/3/85	8	0	4	2	265	
16	8/31/85	7	4	4	1	266	
17	6/28/86	1	6	4	-1	265	40
18	7/16/87	1446	0	4	362	627	361.5
19	4/30/88	17	22	4	-1	626	-1.2
20	8/16/88	26	6	4	5	631	
21	10/21/88	4	2	4	1	632	
22	5/10/89	3	12	4	-2	630	3.2
23	8/12/89	7	3	3	1	631	
24	10/13/89	2	2	3	0	631	
25	5/17/90	3	5	4	-1	630	0.8

STATION 5

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	1	7	4	-2	-2	
2	7/13/83	11	19	4	-2	-4	
3	8/22/83	16	5	3	4	0	
4	10/16/83	9	4	4	1	1	
5	5/9/84	20	6	4	4	5	5
6	5/30/84	2	4	4	-1	4	
7	7/13/84	395	0	4	99	103	
8	7/23/84	110	0	4	28	131	
9	8/24/84	211	0	4	53	184	
10	9/13/84	16	0	4	4	188	
11	10/13/84	1	0	4	0	188	
12	4/28/85	91	11	4	20	208	203
13	6/20/85	24	0	4	6	214	
14	8/3/85	4	1	4	1	215	
15	8/31/85	1	3	4	-1	214	
16	6/28/86	1	5	4	-1	213	5
17	7/16/87	459	0	4	115	328	115
18	4/30/88	24	2	3	7	335	7
19	8/16/88	3	0	3	1	336	
20	10/8/88	1	11	3	-3	333	
21	5/10/89	0	2	3	-1	332	-3
22	8/13/89	4	4	3	0	332	
23	10/13/89	10	0	3	3	335	
24	5/17/90	0	55	3	-18	317	-15

STATION 6

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	5/16/83	0	10	0	--	0	
2	6/21/83	85	0	3	28	28	
3	7/14/83	56	50	3	2	30	
4	8/22/83	3	46	3	-14	16	
5	10/16/83	58	0	3	19	35	
6	5/9/84	46	18	3	9	44	44.7
7	5/31/84	2	1	3	0	44	
8	7/13/84	13	5	3	3	47	
9	8/24/84	1	2	3	0	47	
10	9/13/84	405	0	3	135	182	
11	10/13/84	11	0	3	4	186	
12	3/11/85	143	0	3	48	234	190
13	6/20/85	5	0	1	5	239	
14	8/3/85	0	0	1	0	239	
15	8/31/85	0	5	1	-5	234	
16	6/28/86	200	0	1	200	434	200
17	7/16/87	339	0	1	339	773	339
18	4/30/88	10	0	1	10	783	10
19	6/27/88	0	22	1	-22	761	
20	10/8/88	17	0	1	17	778	
21	5/10/89	0	0	1	0	778	-5
22	8/15/89	5	0	1	5	783	
23	10/13/89	0	3	1	-3	780	
24	5/17/90	25	0	1	25	805	27

STATION 7

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	5/16/83	75	0	4	19	19	
2	6/20/83	30	45	4	-4	15	
3	7/14/83	260	10	4	63	78	
4	8/22/83	109	12	4	24	102	
5	10/16/83	140	1	4	35	137	
6	5/9/84	170	29	4	35	172	171.8
7	5/31/84	76	0	4	19	191	
8	7/13/84	202	0	4	51	242	
9	7/23/84	6	1	4	1	243	
10	8/24/84	258	0	4	65	308	
11	9/13/84	40	13	4	7	315	
12	10/13/84	28	1	4	7	322	
13	3/11/85	112	17	4	24	346	
14	4/28/85	275	0	3	92	438	266
15	6/20/85	1	0	4	0	438	
16	8/3/85	2	0	4	1	439	
17	8/31/85	0	6	4	-2	437	
18	6/28/86	536	3	4	133	570	132
19	7/16/87	675	0	4	169	739	168.8
20	4/30/88	39	17	4	6	745	5.5
21	6/27/88	253	6	4	62	807	
22	10/8/88	258	30	4	57	864	
23	5/10/89	155	1	4	39	903	158
24	8/15/89	27	19	4	2	905	
25	10/13/89	1	19	4	-5	900	
26	5/17/90	11	1	4	3	903	0

STATION 50

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/20/83	67	50	5	3	3	
2	8/22/83	68	1	5	13	16	
3	10/16/83	75	23	5	10	26	
4	5/9/84	212	5	4	52	78	79
5	5/30/84	5	1	5	1	79	
6	7/13/84	14	37	5	-5	74	
7	8/23/84	19	0	5	4	78	
8	9/13/84	18	0	5	4	82	
9	10/13/84	51	2	5	10	92	
10	3/12/85	2	28	5	-5	87	
11	4/25/85	2	2	5	0	87	9
12	6/20/85	104	0	5	21	108	
13	8/3/85	12	0	5	2	110	
14	8/31/85	3	10	5	-1	109	
15	6/28/86	11	9	5	0	109	22
16	7/15/87	95	2	5	19	128	18.6
17	4/30/88	71	18	5	11	139	10.6
18	6/27/88	2	33	5	-6	133	
19	10/8/88	63	79	5	-3	130	
20	5/10/89	148	6	5	28	158	19
21	8/16/89	89	30	5	12	170	
22	10/13/89	121	0	5	24	194	
23	5/17/90	17	94	5	-15	179	20.6

STATION 51

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	5/16/83	132	0	13	10	10	
2	6/21/83	100	179	13	-6	4	
3	7/13/83	1	44	12	-4	0	
4	7/28/83	393	22	12	31	31	
5	8/24/83	125	28	12	8	39	
6	10/16/83	41	57	12	-1	38	
7	5/9/84	138	24	12	10	48	47.7
8	5/31/84	39	1	12	3	51	
9	7/13/84	578	10	12	47	98	
10	7/23/84	647	2	12	54	152	
11	8/23/84	1303	0	12	109	261	
12	9/13/84	279	10	10	27	288	
13	10/15/84	118	5	12	9	297	
14	4/27/85	270	21	12	21	318	270
15	6/19/85	186	28	14	11	329	
16	8/31/85	141	34	14	8	337	
17	6/28/86	75	8	14	5	342	24
18	7/15/87	2363	0	10	236	578	236.3
19	4/28/88	440	73	10	37	615	36.7
20	6/27/88	41	8	10	3	618	
21	8/16/88	13	38	10	-3	615	
22	10/8/88	10	21	10	-1	614	
23	5/10/89	77	7	10	7	621	6.7
24	8/17/89	7	72	10	-7	614	
25	10/13/89	59	15	10	4	618	
26	5/16/90	92	2	9	10	628	7.9

STATION 52

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/21/83	70	15	7	8	8	
2	7/13/83	31	13	7	3	11	
3	7/28/83	156	28	6	21	32	
4	8/24/83	131	6	6	21	53	
5	10/16/83	5	6	6	0	53	
6	5/9/84	19	5	6	2	55	54.8
7	5/31/84	0	0	6	0	55	
8	7/13/84	136	5	7	19	74	
9	7/23/84	393	0	7	56	130	
10	8/23/84	689	0	7	98	228	
11	9/13/84	97	0	7	14	242	
12	10/13/84	9	0	7	1	243	
13	4/27/85	369	4	7	52	295	240
14	6/19/85	133	8	8	16	311	
15	8/31/85	11	7	8	1	312	
16	6/28/86	3	26	8	-3	309	13.3
17	7/15/87	2242	0	8	280	589	280.3
18	4/28/88	147	24	8	15	604	15.4
19	6/27/88	37	19	8	2	606	
20	8/16/88	17	36	8	-2	604	
21	10/8/88	1	23	7	-3	601	
22	5/10/89	3	21	6	-3	598	-6.3
23	8/19/89	56	4	6	9	607	
24	10/13/89	36	11	6	4	611	
25	5/16/90	121	7	7	16	627	29.2

STATION 53

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/28/83	7	7	12	0	0	
2	7/13/83	31	35	12	0	0	
3	8/23/83	45	4	12	3	3	
4	10/15/83	15	7	12	1	4	
5	5/10/84	158	2	12	13	17	17
6	6/1/84	13	11	11	0	17	
7	7/13/84	67	16	12	4	21	
8	7/24/84	116	68	12	4	25	
9	8/24/84	301	4	12	25	50	
10	9/13/84	14	4	12	1	51	
11	10/14/84	11	0	12	1	52	
12	3/12/85	24	48	12	-2	50	
13	4/26/85	358	12	12	29	79	62
14	6/18/85	160	10	12	13	92	
15	7/29/85	22	2	13	2	94	
16	8/31/85	9	15	13	0	94	
17	6/28/86	94	46	13	4	98	19
18	7/15/87	1315	5	13	101	199	101
19	4/30/88	212	58	13	12	211	12
20	6/28/88	247	93	13	12	223	
21	10/8/88	276	29	12	21	244	
22	5/11/89	190	196	12	-1	243	32
23	7/26/89	197	20	13	14	257	
24	10/13/89	46	51	13	0	257	
25	5/16/90	47	17	12	3	260	16

STATION 54

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/28/83	0	0	0	0	0	
2	7/13/83	104	2	4	26	26	
3	8/27/83	115	0	4	29	55	
4	10/15/83	105	9	5	19	74	
5	5/10/84	342	0	5	68	142	142
6	6/1/84	379	0	5	76	218	
7	7/13/84	301	0	5	60	278	
8	8/24/84	127	0	3	42	320	
9	9/16/84	534	0	3	178	498	
10	10/14/84	--	--	--		498	
11	6/18/85	66	0	4	17	515	373
12	7/29/85	2	0	4	1	516	
13	8/31/85	13	0	4	3	519	
14	9/27/86	190	2	4	47	566	51
15	7/15/87	1395	0	4	349	915	349
16	4/30/88	12	6	2	3	918	3
17	6/28/88	84	0	3	28	946	
18	10/9/88	65	0	3	22	968	
19	5/11/89	31	35	3	-1	967	48
20	7/26/89	59	15	4	11	978	
21	10/13/89	29	34	4	-1	977	
22	5/17/90	36	6	4	8	985	17

STATION 55

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/28/83	17	11	9	1	1	
2	7/13/83	546	19	9	59	60	
3	8/23/83	613	4	9	68	128	
4	10/15/83	348	1	9	39	167	
5	5/10/84	1021	48	9	108	275	274
6	6/1/84	674	22	9	72	347	
7	7/13/84	966	0	7	138	485	
8	7/24/84	524	51	9	53	538	
9	8/24/84	195	0	9	22	560	
10	9/13/84	312	12	8	38	598	
11	10/14/84	269	3	9	30	628	
12	3/12/85	824	21	6	134	762	
13	4/26/85	296	1	5	59	821	546
14	6/18/85	408	6	10	40	861	
15	7/29/85	95	9	10	9	870	
16	8/31/85	182	11	10	17	887	
17	6/27/86	554	5	10	55	942	121
18	7/15/87	5093	0	7	728	1670	728
19	4/3/88	0	12	1	-12	1658	-12
20	6/28/88	0	51	3	-17	1641	
21	10/9/88	221	0	3	74	1715	
22	5/11/89	220	0	3	73	1788	130
23	7/26/89	11	0	2	6	1794	
24	10/13/89	209	0	3	70	1864	
25	5/17/90	0	1	3	0	1864	75

STATION 56

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/28/83	245	9	8	30	30	
2	7/13/83	50	28	8	3	33	
3	8/23/83	573	0	8	72	105	
4	10/15/83	311	2	8	39	144	
5	5/10/84	783	7	8	97	241	240
6	6/1/84	176	7	6	28	269	
7	7/13/84	441	6	6	73	342	
8	7/24/84	6	2	4	1	343	
9	8/24/84	83	3	7	11	354	
10	9/13/84	684	0	7	98	452	
11	10/14/84	189	2	5	37	489	
12	3/12/85	517	15	5	100	589	
13	6/18/85	138	6	5	26	615	375
14	7/29/85	86	28	5	12	627	
15	8/31/85	182	3	5	36	663	
16	6/27/86	274	11	5	53	716	100
17	7/15/87	1863	0	5	373	1089	373
18	4/30/88	381	0	3	127	1216	127
19	6/28/88	738	125	5	123	1339	
20	10/9/88	291	3	4	72	1411	
21	5/11/89	97	3	4	24	1435	218
22	7/26/89	23	0	4	6	1441	
23	10/13/89	37	9	4	7	1448	
24	5/17/90	3	9	4	-2	1446	11

STATION 57

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/28/83	22	0	8	3	3	
2	7/13/83	16	4	8	2	5	
3	8/23/83	10	5	8	1	6	
4	10/15/83	22	1	8	3	9	
5	5/10/84	141	3	8	17	26	25
6	6/1/84	2	7	8	-1	25	
7	7/13/84	172	35	8	17	42	
8	7/24/84	141	1	8	18	60	
9	8/24/84	172	5	8	21	81	
10	9/13/84	118	9	8	14	95	
11	10/14/84	11	2	8	1	96	
12	3/12/85	273	21	8	32	128	
13	4/20/85	180	24	6	26	154	128
14	6/18/85	217	0	8	27	181	
15	7/29/85	60	2	8	7	188	
16	8/31/85	28	6	8	3	191	
17	6/28/86	5	26	8	-3	188	34
18	7/15/87	1168	0	8	146	334	146
19	4/30/88	219	36	8	23	357	23
20	6/28/88	30	18	8	2	359	
21	10/9/88	3	34	6	-5	354	
22	5/11/89	25	14	6	2	356	-2
23	7/26/89	2	14	7	-2	354	
24	10/13/89	5	18	7	-2	352	
25	5/16/90	0	30	7	-4	348	-8

STATION 58

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/24/83	0	0	0	0	0	
2	7/13/83	5	12	8	-1	-1	
3	8/23/83	27	1	8	3	2	
4	10/15/83	18	9	8	1	3	
5	5/10/84	43	24	8	2	5	6
6	6/1/84	5	5	8	0	5	
7	7/13/84	11	3	8	1	6	
8	7/24/84	289	2	8	36	42	
9	8/24/84	151	1	8	19	61	
10	9/13/84	2	1	8	0	61	
11	10/14/84	4	1	8	0	61	
12	4/26/85	14	6	7	1	62	57
13	6/18/85	2	3	7	0	62	
14	8/2/85	11	8	7	0	62	
15	8/31/85	6	4	7	0	62	
16	6/28/86	308	9	7	43	105	43
17	7/15/87	704	0	6	117	222	117
18	5/1/88	112	94	6	3	225	3
19	6/28/88	6	8	6	0	225	
20	7/19/88	118	9	6	18	243	
21	10/9/88	177	9	6	28	271	
22	5/11/89	42	5	6	6	277	52
23	7/27/89	10	4	7	1	278	
24	10/14/89	111	43	7	10	288	
25	5/16/90	52	17	7	5	293	16

STATION 59

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/24/83	41	0	4	10	10	
2	7/13/83	7	3	4	1	11	
3	7/28/83	5	0	4	1	12	
4	8/23/83	1	7	4	-2	10	
5	10/15/83	4	2	4	1	11	
6	5/10/84	--	--	4	0	11	11
7	6/1/84	28	11	4	4	15	
8	7/13/84	275	3	4	68	83	
9	7/24/84	2	4	4	-1	82	
10	8/24/84	27	0	4	7	89	
11	9/13/84	1	5	4	-1	88	
12	10/14/84	42	0	4	11	99	
13	4/26/85	3	2	4	0	99	88
14	6/18/85	2	0	4	1	100	
15	8/2/85	4	0	4	1	101	
16	6/28/86	200	30	4	43	144	44
17	7/16/87	807	0	4	202	346	202
18	5/1/88	111	17	4	24	370	24
19	6/28/88	16	1	4	4	374	
20	10/9/88	56	11	4	11	385	
21	5/11/89	4	41	4	-9	376	6
22	7/27/89	3	17	4	-4	372	
23	10/14/89	1	12	4	-3	369	
24	5/16/90	0	8	4	-2	367	8

STATION 60

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/1/83	35	0	1	35	35	
2	7/13/83	21	0	1	21	56	
3	7/28/83	0	4	1	-4	52	
4	8/23/83	4	0	1	4	56	
5	10/15/83	0	4	1	-4	52	
6	5/10/84	9	0	1	9	61	61
7	6/1/84	0	6	1	-6	55	
8	7/13/84	0	2	1	-2	53	
9	7/24/84	2	0	1	2	55	
10	8/24/84	0	1	1	-1	54	
11	9/13/84	0	0	1	0	54	
12	10/14/84	0	0	1	0	54	
13	3/12/85	3	0	1	3	57	
14	4/26/85	0	0	1	0	57	-4
15	6/18/85	0	0	1	0	57	
16	8/1/85	0	0	1	0	57	
17	8/31/85	0	0	1	0	57	
18	6/28/86	35	0	1	35	92	35
19	7/16/87	200	0	1	200	292	200
20	5/1/88	0	6	1	-6	286	-6
21	6/28/88	3	0	1	3	289	
22	10/9/88	0	1	1	-1	288	
23	5/11/89	0	0	1	0	288	2
24	7/27/89	0	11	1	-11	277	
25	10/14/89	0	0	1	0	277	
26	5/16/90	5	0	1	5	282	-6

STATION 61

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	6/1/83	65	0	1	65	65	
2	6/23/83	5	0	1	5	70	
3	7/13/83	2	1	1	1	71	
4	7/28/83	275	137	3	46	117	
5	8/23/83	68	68	2	0	117	
6	10/15/83	0	2	3	-1	116	
7	5/10/84	255	0	3	85	201	201
8	6/1/84	0	0	2	0	201	
9	7/13/84	432	216	3	72	273	
10	7/24/84	--	--	--	--	273	
11	8/24/84	0	0	2	0	273	
12	9/13/84	0	0	1	0	273	
13	10/14/84	0	0	1	0	273	
14	3/12/85	0	0	0	0	273	
15	4/26/85	0	0	0	0	273	72
16	6/18/85	0	0	0	0	273	
17	8/1/85	189	0	5	38	311	
18	8/31/85	10	6	6	1	312	
19	6/28/86	72	7	5	13	325	52
20	7/16/87	1884	0	5	377	702	377
21	5/1/88	34	29	5	1	703	1
22	6/28/88	2	44	5	-8	695	
23	10/9/88	91	5	5	17	712	
24	5/11/89	45	11	5	7	719	16
25	7/27/89	14	1	5	3	722	
26	10/14/89	1	14	5	-3	719	
27	5/16/90	9	13	5	-1	718	-1

STATION 62

Interval	Date	Recession (cm)	Accumulation (cm)	Pins	Average Recession (cm)	Cumulative Recession (cm)	Recession/Year (cm)
1	--	--	--	--	--	--	
2	--	--	--	--	--	--	
3	7/13/83	39	14	5	5	5	
4	7/28/83	59	7	5	10	15	
5	8/23/83	156	5	5	30	45	
6	10/15/83	63	4	5	12	57	
7	5/10/84	86	17	5	14	71	71
8	6/1/84	3	12	5	-2	69	
9	7/13/84	65	4	5	12	81	
10	7/24/84	142	1	5	28	109	
11	8/24/84	95	1	5	19	128	
12	9/13/84	7	0	4	2	130	
13	10/14/84	43	0	4	11	141	
14	3/12/85	77	13	4	16	157	
15	4/26/85	48	39	4	2	159	88
16	6/18/85	55	0	5	11	170	
17	8/1/85	63	4	6	10	180	
18	8/31/85	13	2	6	2	182	
19	6/28/86	13	64	6	-9	173	14
20	7/16/87	844	0	5	169	342	169
21	5/1/88	310	32	5	56	398	56
22	6/28/88	27	9	5	4	402	
23	10/9/88	16	18	5	0	402	
24	5/11/89	15	28	5	-3	399	1
25	7/27/89	21	38	5	-3	396	
26	10/13/89	132	9	5	25	421	
27	5/16/90	5	10	5	-1	420	20

APPENDIX II

BANK RECESSION STATION GEOLOGIC DESCRIPTIONS

EXPLANATION

CCC: - Coarse clast count (areal percent of the beach covered by sediment that is pebble-size or larger).

Geologic Units

 - Oahe Formation.

 - Upper Snow School till.

 - Lower Snow School Formation.

 - Upper Horseshoe Valley till.

 - Lower Horseshoe Valley till.

 - Upper Medicine Hill till.

 - Sentinel Butte Formation channel sandstone.

 - Sentinel Butte Formation mudstone.

 - Sentinel Butte Formation concretion layers.

 - Sentinel Butte Formation clay.

 - Sentinel Butte Formation lignite.

Station #1 **Location:** NW,SW,30,T147N,R84N **Date:** 8/12/89

Current Recession: (1.12 m)/yr. **Interval:** 1983-1990

Geometry:

Orientation: Northeast (40°)

Height: 2.4 m

Slope: >85°

Stratigraphy:

2. Oahe Formation (wind-blown silt).
1. Upper Snow School till.

Structures:

2. Well-developed closely spaced vertical fractures forming a columnar jointing pattern. Vertical fracture frequency of 8/m.
1. Vertical fracture with a frequency of about 3/m. Most are 30-100 cm long. Vertical fractures are directionally dispersed in this area; however, there are two weakly defined preferred orientations at approximately 18° and 86°.

Bank Top Characteristics:

Slope: Flat.

Topography: Low-lying and flat point extending southeast from Lake Sakakawea State Park headland.

Vegetation: Long thick grass.

Wave Factors:

Effective Fetch: 7.5 kilometres (northeast)

Beach Riprap: CCC: 75%, pebble stringers and berms composed of hard cobble-size flat slabs baked by lignite burns.

Shoreline Geometry: Straight northeast-facing shoreline.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle sliding along vertical bank-parallel tension fractures.

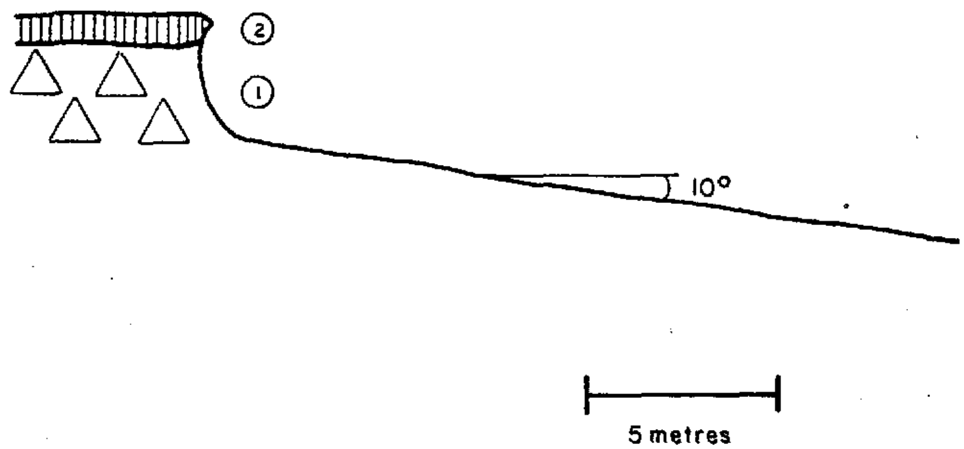


Figure 38. Station 1.

Station #2 **Location:** NE,NE,NE,24,T147N,R85W **Date:** 8/10/89

Current Recession: (0.7 m/yr). **Interval:** 1983-1990

Historical Recession: (1.14 m/yr). **Interval:** 1964-1979

(0.85 m/yr). **Interval:** 1979-1988

Geometry:

Orientation: Northeast (47°)

Height: 7.6 m

Slope: 85°

Stratigraphy:

4. Oahe Formation: 0-1 m discontinuous.
3. Upper Snow School till: 0-1 m thick.
2. Lignite: 0-0.3 m thick.
1. Sentinel Butte mudstone.

Structures:

4. Closely spaced vertical fractures extending through unit.
3. Poorly developed vertical fractures.
2. Dense blocky fracture pattern consisting of short and closely spaced horizontal and vertical fractures perpendicular to bank surface. Contains scattered pieces of petrified wood.
1. Well-defined 0.05-0.3 m bedding and a blocky fracture pattern consisting of poorly developed horizontal fractures and two sets of short vertical fractures oriented at 93° and 149°.

Bank Top Characteristics:

Slope: 5° upslope.

Topography: Flat land sloping gently to the southeast.

Vegetation: Prairie grass and sweet clover.

Wave Factors:

Effective Fetch: 5.1 kilometres northeast.

Beach riprap: CCC: 83%, widely scattered boulders on a clinker pebble beach, mostly pebbles, approximately 2% boulders.

Shoreline geometry: Straight northwest to southeast trending shoreline along large headland projecting northward into the lake.

Dominant Bank Failure Mechanisms: Top half of bank failing due to high-angle slides and topples along large vertical bank-parallel fractures. Small-scale block toppling is the dominant failure mechanism for the bottom half.

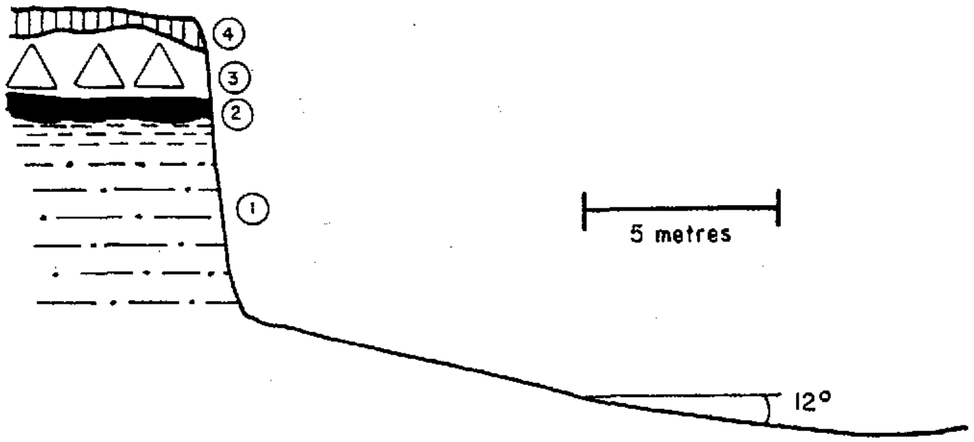


Figure 39. Station 2.

Station #3 **Location:** NW,SE,NW,24,T147N,R85W **Date:** 8/14/89

Current Recession: (0.76 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: North facing (350°)

Height: 3.4 m

Slope: 25-90°

Stratigraphy:

2. Oahe Formation (wind-blown silt).
1. Upper Snow School till.

Structures:

2. Well-developed closely-spaced vertical fractures forming a columnar jointing pattern. Vertical fracture frequency 10/m.
1. Vertical fractures frequency about 3/m. Most are 30-100 cm long. Vertical fractures are directionally dispersed in this area; however, there are two weakly-defined preferred orientations at approximately 18° and 86°.

Bank Top Characteristics:

Slope: Flat.

Topography: Flat to gently sloping dissected headland.

Vegetation: Short grass (picnic and camping site).

Wave Factors:

Effective Fetch: 1.9 kilometres (northeast).

Beach Riprap: CCC: 15%, scattered stringers of gravel.

Shoreline Geometry: Short north-facing section of an irregular, dissected, and low-lying shoreline on the Lake Sakakawea State Park headland. This shoreline is protected from wave action by several islands to the north.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle sliding along vertical bank-parallel tension fractures.

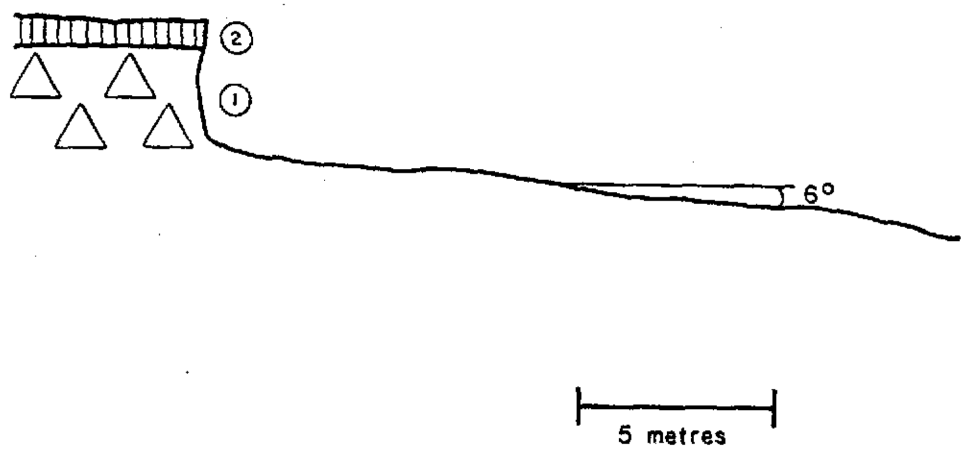


Figure 40. Station 3,

Station #4 **Location:** SW,NW,25,T147N,R85W **Date:** 8/12/89

Current Recession: (0.90 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: North

Height: 30 m

Slope: 70-80°

Stratigraphy:

2. Thin discontinuous Oahe Formation (wind-blown silt).
1. Upper Snow School till.

Structures:

2. Well-developed closely spaced vertical fractures forming a columnar jointing pattern. Vertical fracture frequency is approximately 10/m.
1. Vertical fractures with a frequency of about 4.5/m. Most fractures are 30 to 100 cm long. Vertical fractures are directionally dispersed in this area; however, there are two weakly defined preferred orientations at approximately 18° and 86°.

Bank Top Characteristics:

Slope: Flat

Topography: End of a flat point extending northwest. This area is in a protected bay used for the Lake Sakakawea State Park Boat Marina. Topography is flat to slightly sloping and dissected.

Vegetation: Short grass in a parking area and short-grass prairie.

Wave Factors:

Effective Fetch: 1.0 kilometres (northwest).

Beach Riprap: CCC: 50%, depositional beach composed of sand and gravel with scattered cobbles and boulders.

Shoreline Geometry: Tip of a narrow northwest-facing point in a protected bay.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along vertical bank-parallel tension fractures.

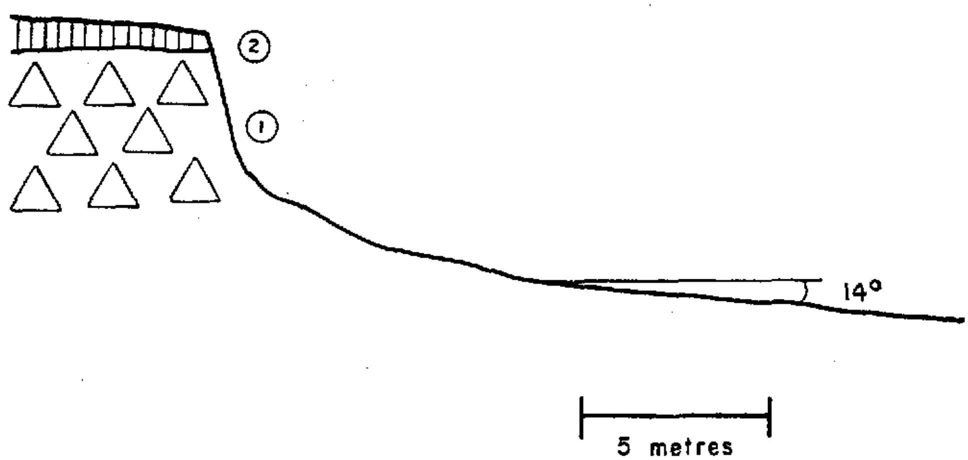


Figure 41. Station 4.

Station #5 **Location:** NW,NE,SW,25,T147N,R85W **Date:** 8/13/89

Current Recession: (0.45 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: West-northwest

Height: 4.6 m

Slope: 75-90°

Stratigraphy:

2. Upper Snow School till.
1. Lower Snow School Formation (thinly cross-bedded sand).

Structures:

2. Vertical fractures with a frequency of about 3.0/m. Most fractures are 30-100 cm long. Vertical fractures are directionally dispersed; however, there are two weakly-defined preferred orientations at 8° and 86°.
1. Thin (<1-3 cm) near-horizontal cross-beds. Vertical fractures mostly 30-100 cm long. Vertical fracture frequency approximately 4.0/m. Vertical fractures are directionally dispersed, but there are two preferred orientations in this area at 18° and 86°.

Bank Top Characteristics:

Slope: Upslope from bank 3-5°.

Topography: Flat dissected headland sloping slightly to the west toward a flooded tributary valley.

Vegetation: Short-grass prairie.

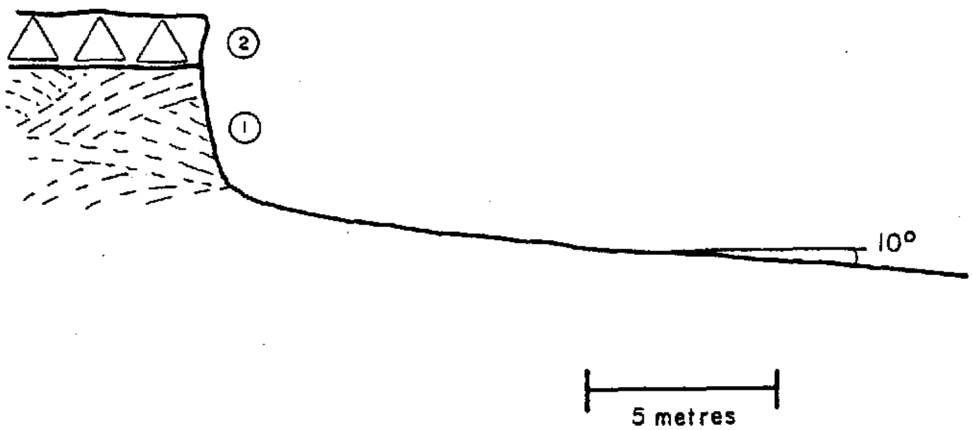
Wave Factors:

Effective Fetch: 0.5 kilometres (west).

Beach Riprap: CCC: 70%. Mainly a depositional beach composed of layers of sand and gravel with scattered stringers of flat cobble size pieces of hard mudstone baked by lignite burns.

Shoreline Geometry: Low west-facing shoreline in a narrow bay.

Dominant Bank Failure Mechanisms: Minor toppling at the top one to two metres of the bank in the Upper Snow School till.



<u>Figure 42</u>. Station 5.

Station #6 **Location:** SE,NE,NE,21,T147,R85W **Date:** 8/15/89

Current Recession: (1.15 m/yr.) **Interval:** 1983-1990

Geometry:

Orientation: North-northeast (015°)

Height: 18 m

Slope: 70-80°

Stratigraphy: 1. Upper Snow School till.

Structures:

1. Well-developed vertical fractures, columnar jointing pattern is apparent in the upper third of the bank, poorly developed horizontal fractures, and scattered silt inclusions and sand and gravel lenses. Vertical fractures frequency approximately 2.4/m. Horizontal fracture frequency approximately 2.5/m. Most vertical fractures are 30-100 cm long. Some are up to 500 cm long. Vertical fractures are directionally dispersed; however, there is one well-defined fracture set oriented at 172° and a dispersed set oriented at approximately 111°.

Bank Top Characteristics:

Slope: Flat in the direction away from the bank edge and steep down slope in either direction parallel to the bank.

Topography: Crest of a steep hill. This area is hilly and dissected.

Vegetation: Short grass. Area formerly grazed and cultivated.

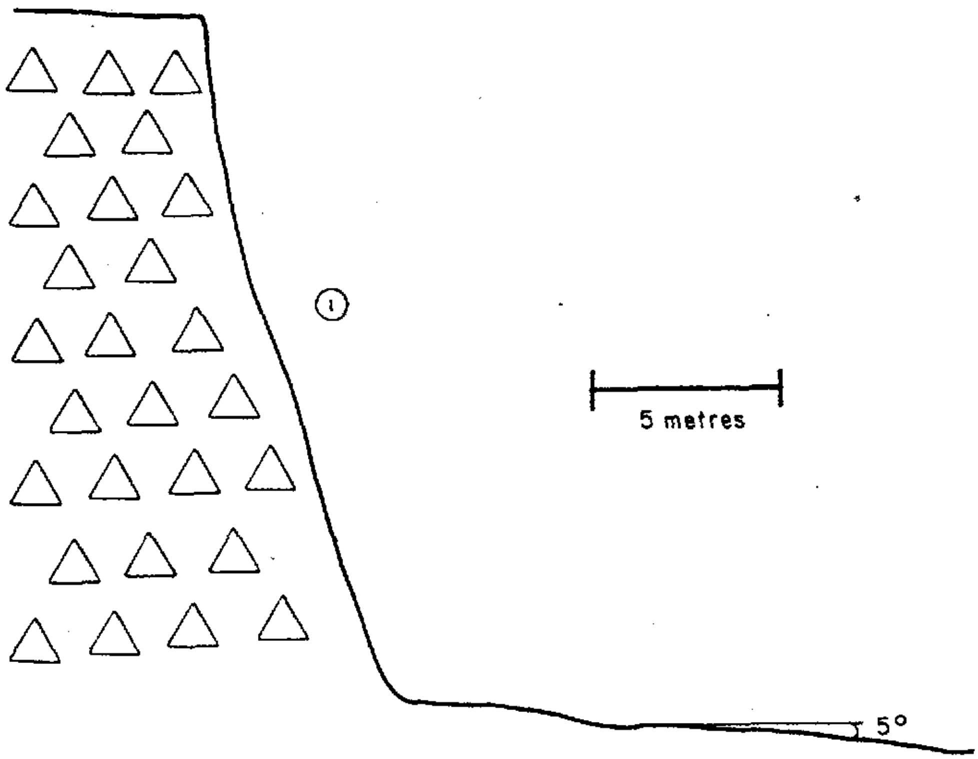
Wave Factors:

Effective Fetch: 5.0 kilometres (north).

Beach Riprap: CCC: 50%, mainly cobble and boulder lag from eroded till.

Shoreline Geometry: Middle of a small north-facing bay along a southwest to northeast trending dissected shoreline. The bay is exposed to a northerly fetch.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical bank-parallel tension cracks.



<u>Figure 43</u>. Station 6.

Station #7 **Location:** SE,NE,NE,21,T147,R85W **Date:** 8/15/89

Current Recession: (1.29 m/yr.) **Interval:** 1983-1990

Geometry:

Orientation: North-northeast (15°)

Height: 15 m

Slope: 70-80°

Stratigraphy:

2. Upper Snow School till.
1. Lower Snow School formation.

Structures:

2. Well-developed vertical fractures. Columnar jointing pattern is apparent in the upper third of the bank. Poorly developed horizontal fractures. Scattered silt inclusion and sand and gravel lenses. Vertical fracture frequency approximately 2.4/m. Horizontal frequency approximately 2.5/m. Most vertical fractures are 30-100 cm long. Some are up to 500 cm long. Vertical fractures are directionally dispersed; however there is one well-defined fracture set oriented at 172° and a dispersed set oriented at approximately 111°.

1. Thin (<1cm-5cm) cross-bedded sand and silt with larger lignite clasts. Fractures are not well-developed in this unit.

Bank Top Characteristics:

Slope: Upslope from bank edge 2°-5°.

Topography: Side of a steep hill. The topography is hilly and dissected.

Vegetation: Short grass, formerly grazed.

Wave Factors:

Effective Fetch: 5.0 Kilometres (north).

Beach Riprap: CCC: 50%, mainly cobble and boulder lag from eroded till.

Shoreline Geometry: Middle of a small north facing bay along a southwest- to northeast-trending dissected shoreline. The bay is exposed to a northerly fetch.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along vertical tension cracks.

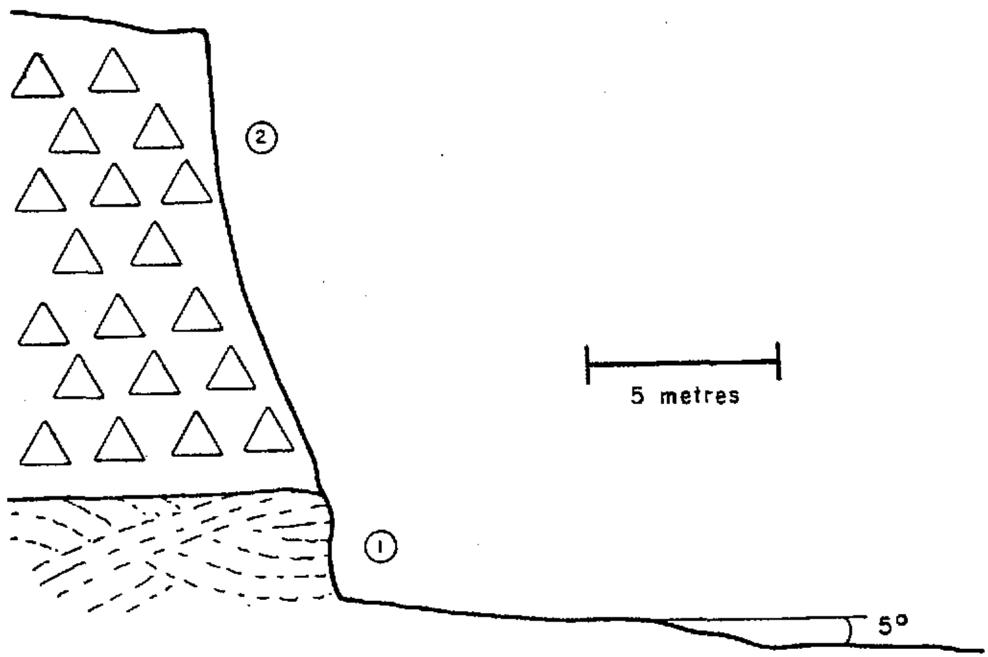


Figure 44. Station 7.

Station #50 **Location:** SW,SW,34,T147,R84W **Date:** 8/16/89

Current Recession: (0.25 m/yr). **Interval:** 1983-1990

Historical Recession: (1.9 m/yr). **Interval:** 1969-1979
(0.2 m/yr). **Interval:** 1979-1988

Geometry:

Orientation: West-northwest (290°)

Height: 18 m

Slope: 75°

Stratigraphy:

4. Pebble till 0-2 m thick and discontinuous.
3. Interbedded Sentinel Butte formation mudstone, limestone, sandy mudstone, and concretionary limestone lenses and channels.
2. Sentinel Butte Lignite.
1. Sentinel Butte mudstone. Clay-rich facies highly desiccated.

Structures:

3. Strong bedding and short vertical fractures well-indurated limestone beds and concretions.
2. Dense blocky fracture pattern consisting of closely spaced horizontal and vertical fractures scattered pieces of petrified wood.
1. Closely spaced bank-perpendicular desiccation cracks forming a block fracture pattern.

Bank Top Characteristics:

Slope: 15° uphill for 30 m then flat.

Topography: Steep slope up from river valley to gently sloping flat land. Landscape is dissected near valley.

Vegetation: Short-grass prairie including cactus and buckbrush.

Wave Factors:

Effective Fetch: 4.5 miles (northwest wind).

Beach Riprap: CCC: 62%, mostly large well-indurated limestone and sandstone slabs weathered from bank. Also, glacial boulders and petrified wood.

Shoreline Geometry: Steep dissected NNE to SSW trending shoreline.

Dominant Bank Failure Mechanisms: Small block falls and larger high-angle topples along vertical bank-parallel fractures at the top few metres of the bank.

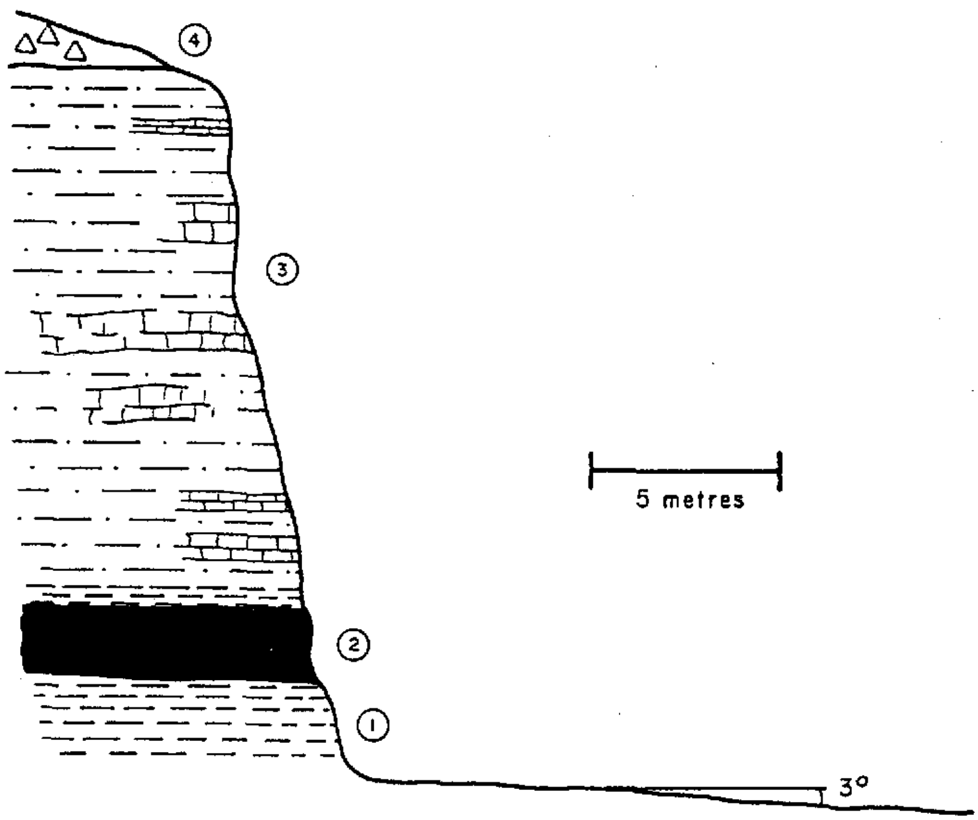


Figure 45. Station 50.

Station #51 **Location:** NW,NE,NW,22,T147N,R84W **Date:** 8/17/89

Current Recession: (0.90 m/yr). **Interval:** 1983-1990

Historical Recession: (5.85 m/yr). **Interval:** 1969-1979

Geometry:

Orientation: South-facing side of point 175°. West-facing side 268°.

Height: 6.7 m

Slope: Stepped slope 70-90°.

Stratigraphy:

3. Upper Horseshoe Valley till.
2. Lower Horseshoe Valley Formation (loose sand and gravel).
1. Upper Medicine Hill till.

Structures:

3. Columnar jointing pattern consisting of large, well-developed, and widely spaced vertical fractures. Two vertical fracture sets here are oriented at 28° and 150°. The average vertical fracture frequency is approximately 2.0/m. Many vertical fractures are over 100 cm long.
1. Well-developed horizontal, oblique and vertical fractures. Horizontal fracture frequency 5.3/m. Vertical fracture frequency 8.8/m. One dominant vertical fracture set oriented at 10°, and two more vertical fracture sets at 75° and 148°. Most of the vertical fracture are 20- 60 cm long.

Bank Top Characteristics:

Slope: Flat

Topography: Small point extending out from Wolf Creek headland. Gently undulating landscape.

Vegetation: Short grass.

Wave Factors:

Effective Fetch: 9.2 kilometres (northwest).

Beach Riprap: CCC: 44%, 20% boulders 24% cobbles and pebbles.

Shoreline geometry: Small point extending westward.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along vertical fractures in the Upper Horseshoe Valley till.

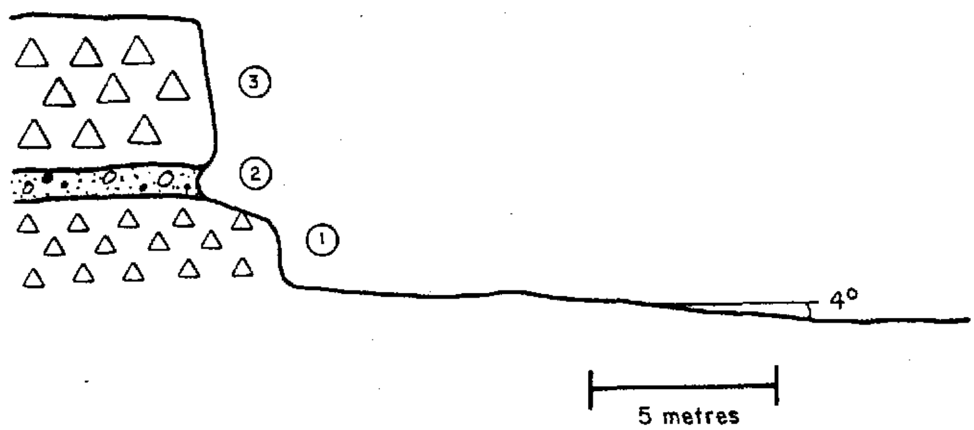


Figure 46. Station 51.

Station #52 **Location:** NE,NE,NW,22,T147N,R84W **Date:** 8/19/89

Current Recession: (0.90 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: Bank faces south-southwest to northwest 195°-300° along a small point.

Height: 7.0 m

Slope: 85°

Stratigraphy:

2. Oahe Formation (Wind-blown silt).
1. Upper Horseshoe Valley Till.

Structures:

2. Columnar jointing pattern consisting of well-developed, closely spaced vertical fractures.
1. Columnar jointing pattern consisting of long, well-developed, and widely spaced vertical fractures. Two vertical fracture sets and oriented at 28° and 150°. Average vertical fracture frequency 2.0/m. Many vertical fractures are over 100 cm long.

Bank Top Characteristics:

Slope: Slightly up hill slope 1° to 2° away from bank.

Topography: Gently rolling topography. Dissected near lake.

Vegetation: Short-grass prairie.

Wave Factors:

Effective Fetch: 9.2 kilometres (northwest).

Beach Riprap: CCC: 70-75%, 1-5% boulders, 30-50% cobbles, 15-40% pebbles.

Shoreline Geometry: Small point extending westward from the Wolf Creek Point headland. The shoreline configuration is irregular in this area. Small bays on either side of this station.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical fractures in the Upper Horseshoe Valley till.

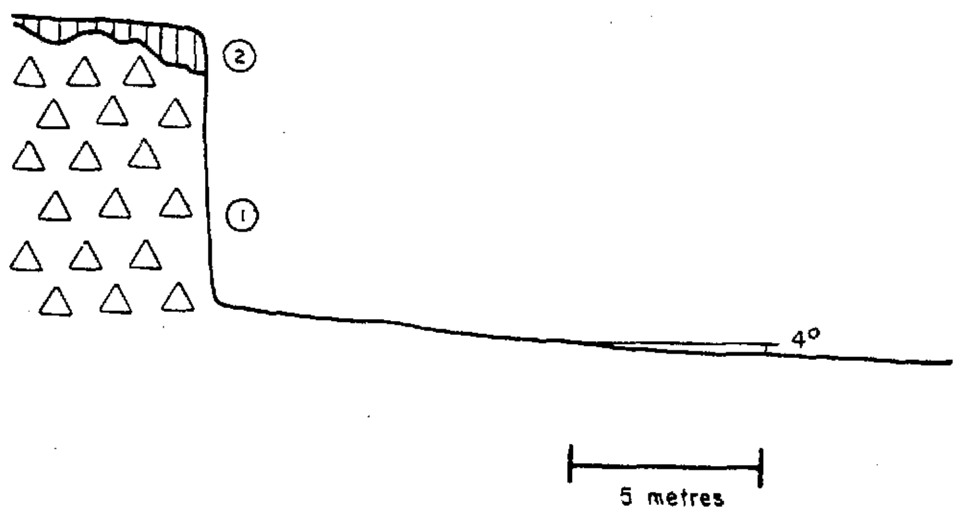


Figure 47. Station 52.

Station #53 **Location:** SW,NW,4,T147,R84W **Date:** 8/20/89

Current Recession: (0.37 m/yr). **Interval:** 1983-1990

Historical Recession: (0.14 m/yr). **Interval:** 1979-1988

Geometry:
Orientation: Southwest (230°)

Height: 13.7 m

Slope: 80°

Stratigraphy:
2. Upper Medicine Hill till.
1. Sentinel Butte Formation mudstone.

Structures:
2. Well-developed vertical, horizontal, and oblique fractures. Horizontal fracture frequency 4.5/m. Vertical frequency is 2.5/m. Two vertical fracture sets oriented at 87° and 161°. Most vertical fracture are 20-60 cm long. Scattered gravel lenses.
1. Blocky fracture pattern consisting of closely spaced, well-developed vertical fractures interesting weakly developed horizontal fracture. Horizontal and vertical fracture frequencies about 4.5/m. Most vertical fracture are 30-80 cm long. Four vertical fracture sets oriented at 6°, 91°, 48°, and 139°.

Bank Top Characteristics:
Slope: Flat.

Topography: Flat headland.

Vegetation: Short-grass prairie.

Wave Factors:
Effective Fetch: 6.6 kilometres (South and southwest).

Beach Riprap: CCC: 71%, boulders 50%, pebbles and cobbles 31%.

Shoreline Geometry: Tip of southeast extending point extending from the Fort Stevenson State Park headland. Mostly straight southwest-facing shoreline.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle slides at the top few metres of the bank. Thaw failure and runoff at bank surface.

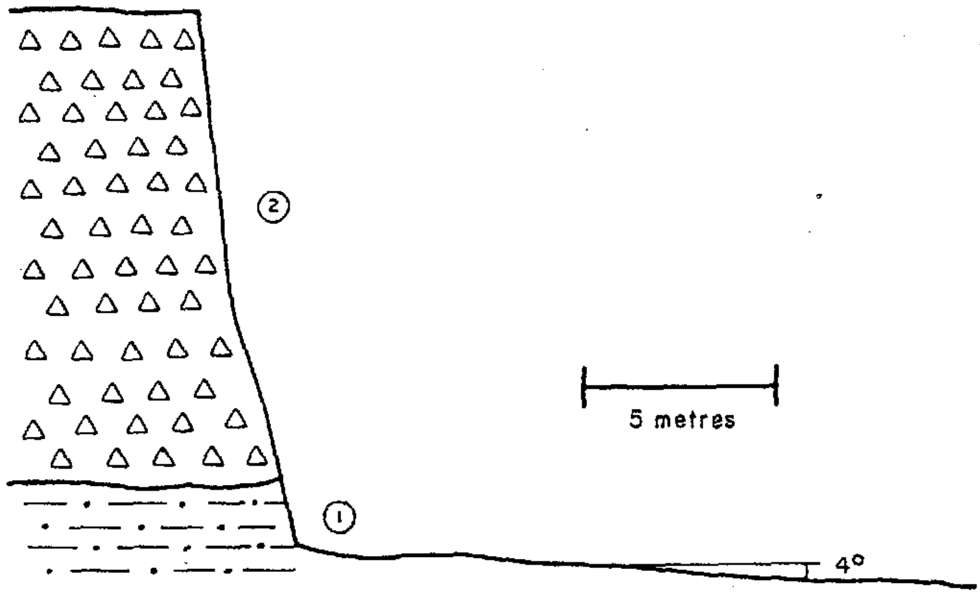


Figure 48. Station 53.

Station #54 **Location:** SE,31,T148N,R84W **Date:** 8/20/89

Current Recession: (1.40 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: Southwest

Height: 3.7 m

Slope: 75-80°

Stratigraphy:

1. Sentinel Butte mudstone (clay-rich facies) with several thin (5-10 cm) lignite beds.

Structures:

1. Very closely spaced desiccation cracks on bank surface. Because of the highly weathered character of this clay-rich material it was not possible to observe primary bank fractures at this site. Vertical fracture sets are oriented at 6°, 91°, 48°, and 139°.

Bank Top Characteristics:

Slope: First 10 metres from bank edge flat, then steep rise up to flat highland.

Topography: Flat headland, slightly dissected near lake.

Vegetation: Thick grass and alder brush.

Wave Factors:

Effective Fetch: 9.0 kilometres (southwest).

Beach Riprap: CCC: 1-3%, cobbles, pebbles, and small pieces of petrified wood. Discontinuous patches of sand, mudstone, and lignite beach.

Shoreline Geometry: Straight northwest to southwest trending shoreline.

Dominant Bank Failure Mechanisms: Frost action, sheet wash, and chemical weathering of clay.

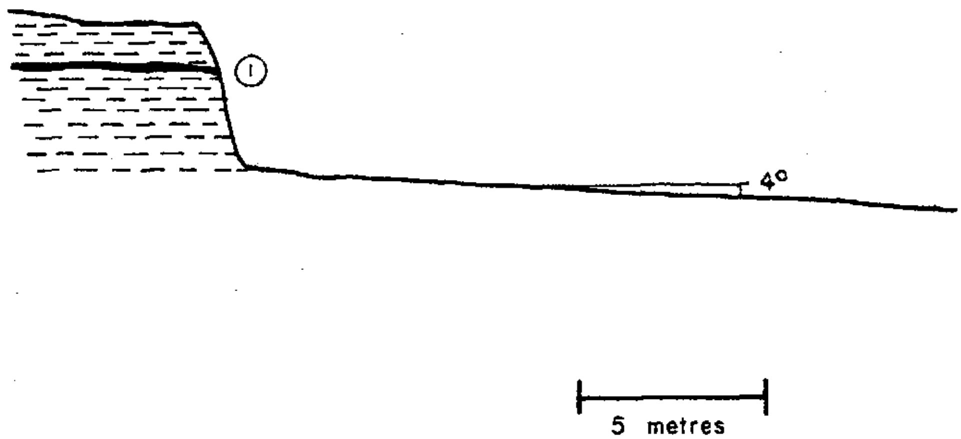


Figure 49. Station 54.

Station #55 **Location:** SE,31,T148N,R84W **Date:** 8/21/89

Current Recession: (2.66 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: Southwest

Height: 11 m

Slope: 80-85°

Stratigraphy:

3. Thin (0-40 cm) discontinuous layer of Oahe Formation (wind-blown silt).
2. Upper Snow School till.
1. Sentinel Butte mudstone.

Structures:

3. Well-developed closely spaced vertical fractures with a columnar jointing pattern.
2. Vertical fractures with a columnar jointing pattern.
1. Blocky fracture pattern consisting of well-developed vertical fractures intersected by bedding planes and poorly developed horizontal fractures. Vertical and horizontal fracture frequencies are four to five fractures/metre. Most vertical fractures are 30-80 cm long. Well developed 2-15 cm bedding. Four vertical fracture sets in this area are oriented at 6°, 91°, 48°, and 139°.

Bank Top Characteristics:

Slope: Flat.

Topography: Slightly dissected headland

Vegetation: Short grass and gravel. Park maintenance facility was formerly located here.

Wave Factors:

Effective Fetch: 9.0 kilometres (southwest).

Beach Riprap: CCC: 1-3%, cobbles, pebbles, and small pieces of petrified wood.

Shoreline Geometry: Straight northwest to southeast trending shoreline.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical bank-parallel tension cracks.

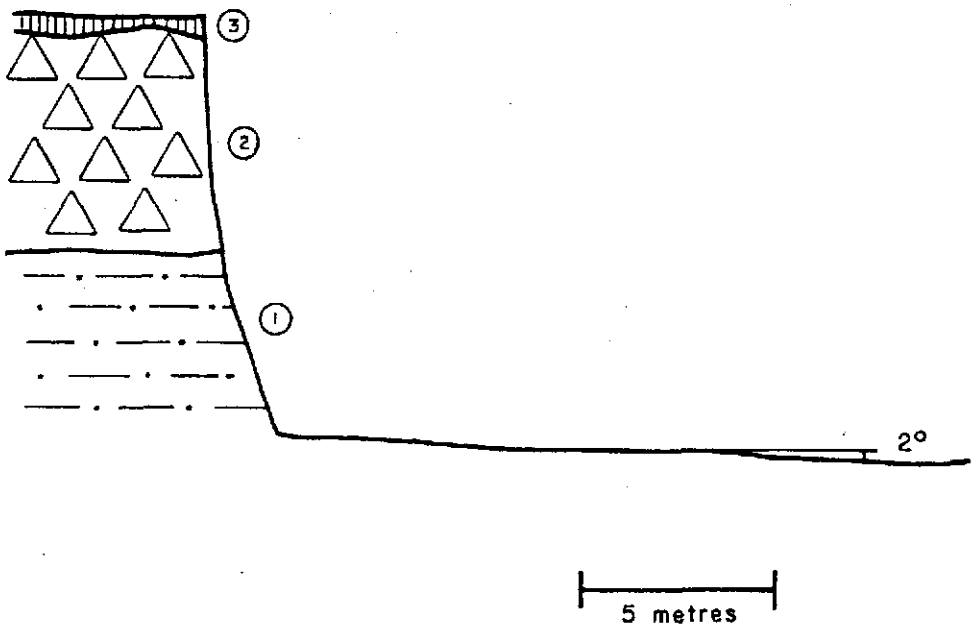


Figure 50. Station 55.

Station #56 Location: NE,SW,31,T148N,R84W **Date:** 8/21/89

Current Recession: (2.06 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: Southwest (225°)

Height: 12 m

Slope: 80-85°

Stratigraphy:

3. Upper Snow School till.
2. Sentinel Butte Formation lignite and clay.
1. Sentinel Butte Formation mudstone.

Structures:

3. Prominent columnar jointing pattern consisting of long vertical fractures greater than 100 cm. Most vertical fractures are 30-100 cm. Vertical fracture frequency approximately 2.5/m.
2. Very closely spaced bank-perpendicular horizontal and vertical desiccation fractures.
1. Blocky fracture pattern consisting of well-developed vertical fractures intersecting horizontal bedding planes and poorly developed horizontal fractures. Vertical and horizontal fracture frequencies are approximately 5.0/m. Most vertical fractures are 30-80 cm long. Four distinct vertical fracture sets are oriented at 6°, 91°, 48°, and 139°.

Bank Top Characteristics:

Slope: Flat.

Topography: Flat to slightly-sloping and dissected highland on the Fort Stevenson State Park headland.

Vegetation: Long grass.

Wave Factors:

Effective Fetch: 9.9 Kilometres (southwest).

Beach Riprap: CCC: 20%, cobble pebble stringers 10%. Scattered large spherical concretions and boulder lag 10%.

Shoreline Geometry: High straight southwest-facing shoreline along the Fort Stevenson State Park Headland.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical bank-parallel fractures in the Upper Snow School till extending down into the Sentinel Butte Formation.

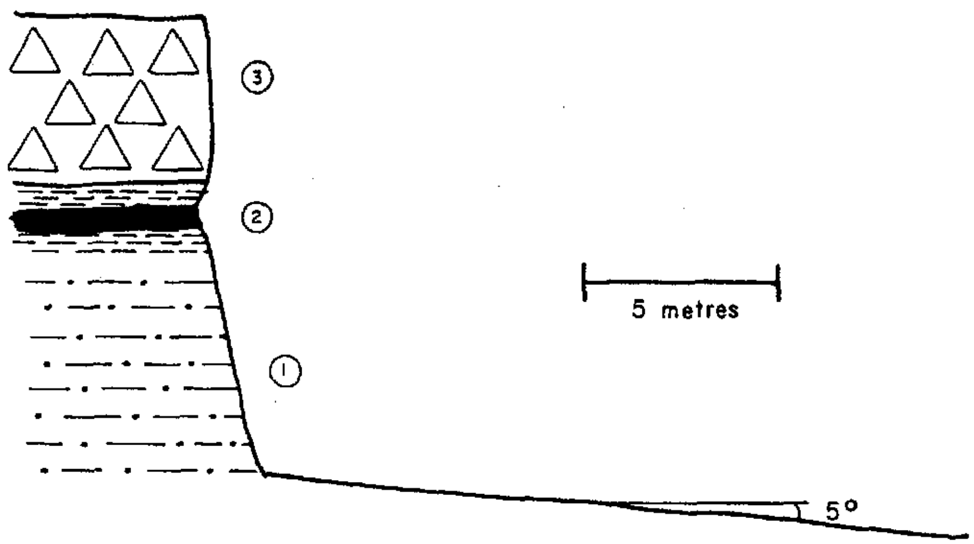


Figure 51. Station 56.

Station #57 **Location:** SE,NW,31,T148N,R84W **Date:** 8/24/89

Current Recession: (0.49 m/yr). **Interval:** 1983-1990

Geometry:
Orientation: West-southwest (255°)

Height: 12 m

Slope: 80-85°

Stratigraphy:
3. Upper Snow School till.
2. Sentinel Butte Formation channel sandstone and interbedded concretionary lenses.
1. Sentinel Butte Formation mudstone and interbedded lignite at beach level.

Structures:
3. Prominent columnar jointing pattern consisting of vertical fractures greater than 100 cm long. Most vertical fractures are 30-100 cm long. Vertical fractures frequency about 2.5/m.
2. 5-50 cm near-horizontal cross-bedding. Horizontal fractures very poorly developed, frequency 1.8/m. Vertical fractures are well-developed, frequency 1.6/m. Most vertical fractures are 30-80 cm long and terminate at intersections with bedding contacts or 15-50 cm thick concretionary lenses. Four distinct vertical fracture sets oriented at 6°, 91°, 48°, and 139°.

Bank Top Characteristics:
Slope: Flat.

Topography: Flat dissected upland sloping gently westward.

Vegetation: Short grass.

Wave Factors:
Effective Fetch: 9.0 Kilometres (South and southwest)

Beach Riprap: CCC: 25%, cobble and boulder lag from eroded till about 10%.

Shoreline Geometry: Straight west-southwest facing shoreline near the tip of a small northwest-facing point on the Fort Stevenson State Park peninsula.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical bank-parallel tension fractures in the Upper Snow School till and extending down into the Sentinel Butte Formation.

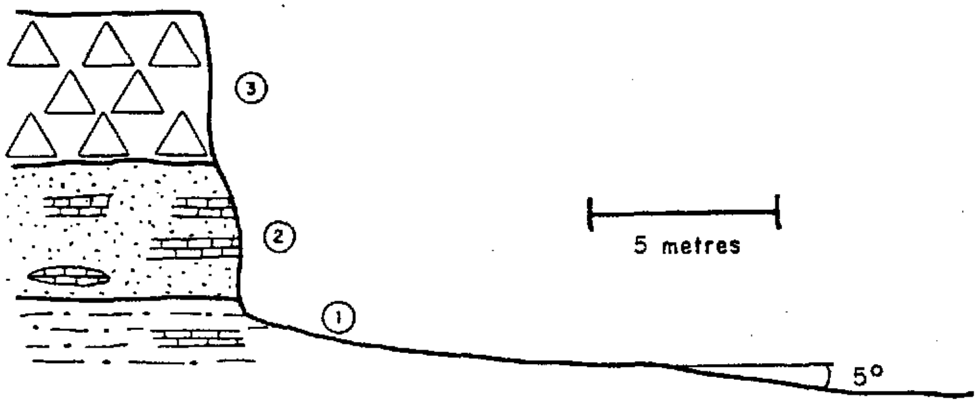


Figure 52. Station 57.

Station #58 **Location:** NW,NW,NW,3,T147N,R85W **Date:** 11/25/89

Current Recession: (0.42 m/yr). **Interval:** 1983-1990

Historical Recession: (<0.10 m/yr). **Interval:** 1964-1979

(<0.10 m/yr). **Interval:** 1977-1988

Geometry:

Orientation: South (170°)

Height: 5.5 m

Slope: 68°

Stratigraphy:

2. Large Upper Medicine Hill silt inclusion.
1. Upper Medicine Hill till.

Structures:

2. Thin bedding and poorly developed and widely spaced vertical fractures.
1. Scattered silt lenses; well-developed horizontal, oblique, and vertical fractures. Horizontal and vertical fracture frequencies approximately 6/m. Three vertical fracture sets consisting of (10-60 cm) fractures of oriented at 47°, 85°, and 147°. Mineral coatings on most fracture surfaces.

Bank Top Characteristics:

Slope: Slight, 2-3°, upslope.

Topography: Side of small ridge with a shallow valley to the east.

Vegetation: Prairie-grass.

Wave Factors:

Effective Fetch: 4.6 miles (south wind).

Beach Riprap: CCC: 65%, boulders 5%, cobbles 60%.

Shoreline Geometry: Straight and south facing.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle slides at the top one to two metres. Thaw failure and sheet wash.

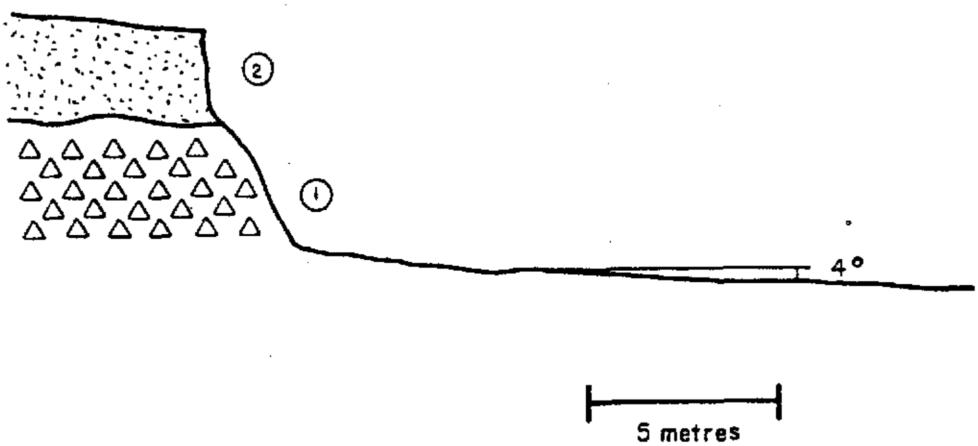


Figure 53. Station 58.

Station #59 **Location:** NE,NE,NE,4,T147N,R85W **Date:** 11/25/89

Current Recession: (0.52 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: South

Height: 7.6 m

Slope: 80-90°

Stratigraphy:

1. Upper Medicine Hill till.

Structures:

1. Well-developed horizontal, vertical, and oblique fractures, most are closed and filled with mineral material. Horizontal fracture frequency 3.6/m. Vertical fracture frequency 6.7/m. Most vertical fractures are 20-60 cm long. There are three near-vertical sets oriented at 85°, 47° and 130°. Scattered small silt and gravel lenses.

Bank Top Characteristics:

Slope: Flat.

Topography: Gently rolling dissected.

Vegetation: Short-grass prairie.

Wave Factors:

Effective Fetch: 6.9 kilometres (southeast to southwest).

Beach Riprap: CCC: 70%, cobbles 10-70% boulders 5-10%.

Shoreline Geometry: Point of a small headland along a dissected shoreline.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle sliding along small bank-parallel tension cracks at the top one to two metres. Sheet wash and thaw failure.

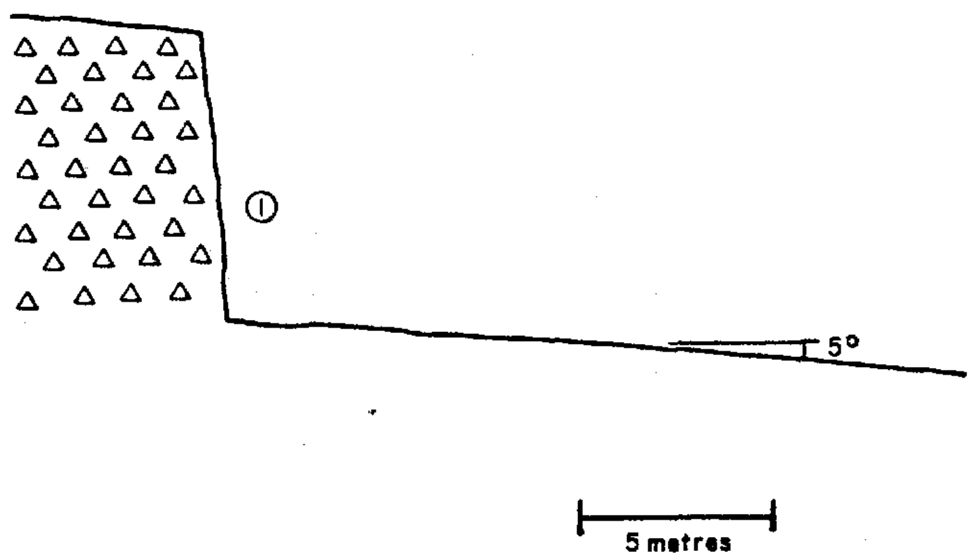


Figure 54. Station 59.

Station #60 **Location:** NE,NE,6,T147N,R85W **Date:** 10/14/89

Current Recession: (0.40 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: East-northeast (70°)

Height: 7.6 m

Slope: 75°

Stratigraphy:

3. Upper Horseshoe Valley till.
2. Sentinel Butte Formation Lignite and clay.
1. Sentinel Butte Formation mudstone.

Structures:

3. Large widely spaced vertical fractures (columnar jointing pattern). Horizontal fracture frequency <1/m. Vertical fracture frequency 2.6/m. Many vertical fractures >100 cm long. Two vertical sets at 152° and 35° and a third weakly defined set at 0°.
2. Closely spaced horizontal and vertical desiccation cracks in lignite and adjacent clay. Vertical and horizontal frequencies about 20/m.
1. Blocky fracture pattern with well-developed vertical fractures intersected by bedding conducts and weak horizontal fractures. Most vertical fractures 30-80 cm long. Vertical and horizontal frequencies about 5/m. Four vertical sets at 3°, 92°, 42°, 140°.

Bank Top Characteristics:

Slope: Side of hill, upslope 10-20°.

Topography: Hilly dissected headland.

Vegetation: Short-grass prairie, minor buckbrush.

Wave Factors:

Effective Fetch: 5.0 kilometres (southeast).

Beach Riprap: CCC: 10%, pebble stringers 5%, cobbles and small petrified wood pieces 5%.

Shoreline Geometry: Straight east-facing shoreline of a small point extending south from a hilly dissected headland.

Dominant Bank Failure Mechanisms: Minor toppling and high-angle sliding along bank-parallel tension cracks at the upper 1-2 metres. Mostly thaw failure and sheet wash.

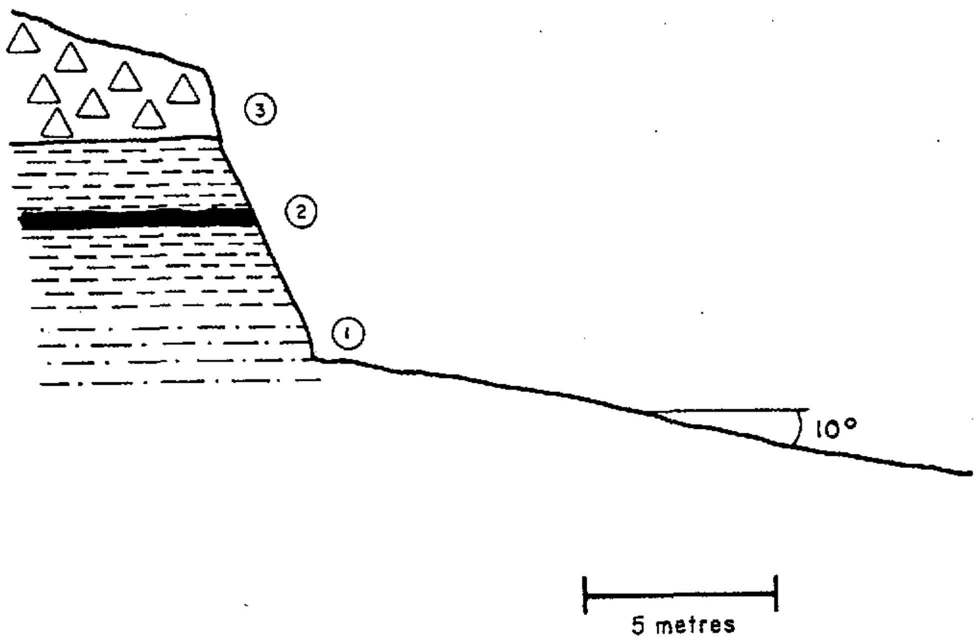


Figure 55. Station 60.

Station #61 **Location:** NE,NE,6,T147N,R85W **Date:** 10/14/89

Current Recession: (1.02 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: South (180°)

Height: 7.9 m

Slope: 80°

Stratigraphy:

3. Upper Horseshoe Valley till.
2. Sentinel Butte Formation lignite and clay.
1. Sentinel Butte Formation mudstone.

Structures:

3. Large vertical fractures (columnar jointing pattern). Horizontal fracture frequency <1/m. Vertical frequency 2.6/m. Many vertical fractures >100 cm. Three vertical sets at 152°, 35°, and 0°.
2. Closely spaced horizontal and vertical desiccation cracks (20 /m).
1. Blocky fracture pattern with well-developed vertical fractures intersected by bedding contacts and weak horizontal fractures. Most vertical fractures (30-80 cm). Vertical and horizontal frequencies 5/m. Four vertical sets at 3°, 92°, 42°, and 140°.

Bank Top Characteristics:

Slope: Upslope from bank 1-3°.

Topography: Hilly dissected headland.

Vegetation: Short-grass prairie.

Wave Factors:

Effective Fetch: 6.0 kilometres (south and southeast).

Beach Riprap: CCC: 5%, boulders, cobbles, and petrified wood.

Shoreline Geometry: Tip of south-facing point extending from a large dissected and hilly headland.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large bank-parallel vertical fractures in the Upper Horseshoe Valley till extending down into the Sentinel Butte Formation.

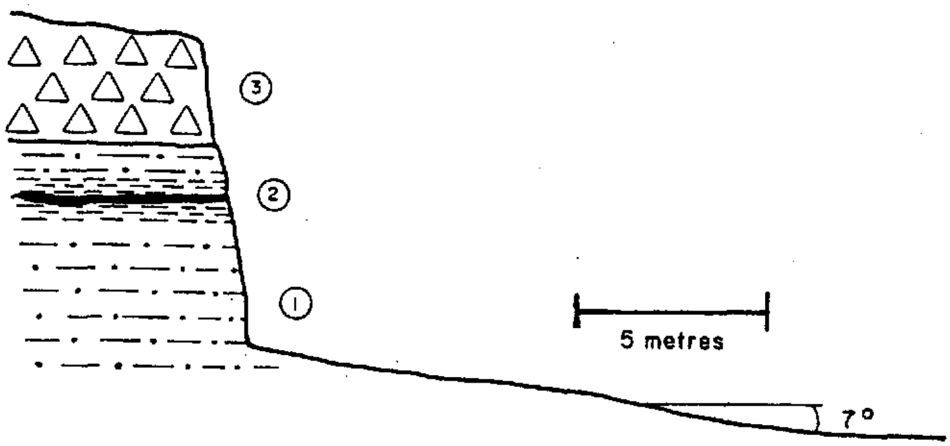


Figure 56. Station 61.

Station #62 **Location:** NE,NE,6,T147N, R85W **Date:** 10/14/89

Current Recession: (0.60 m/yr). **Interval:** 1983-1990

Geometry:

Orientation: West

Height: 11 m

Slope: 80-90°

Stratigraphy:

2. Upper Horseshoe Valley till.
1. Sentinel Butte Formation mudstone with minor interbedded limestone lenses.

Structures:

2. Large vertical fractures (columnar jointing pattern). Horizontal fracture frequency <1/m. Vertical fequency 2.6/m. Many vertical fractures >100 cm. Three vertical sets at 152°, 35°, and 0°.
1. Blocky fracture pattern with well-developed vertical fractures intersected by weak horizontal fractures and bedding. Most vertical fractures are 30-80 cm long. Vertical and horizontal frequencies about 5/m, and much higher in the lignite. Four vertical fracture sets at 3°, 92°, 42°, and 140°.

Bank Top Characteristics:

Slope: Slight upslope from bank edge 1-5°.

Topography: Side of a hill on a hilly headland.

Vegetation: Short-grass prairie. Abundant cactus.

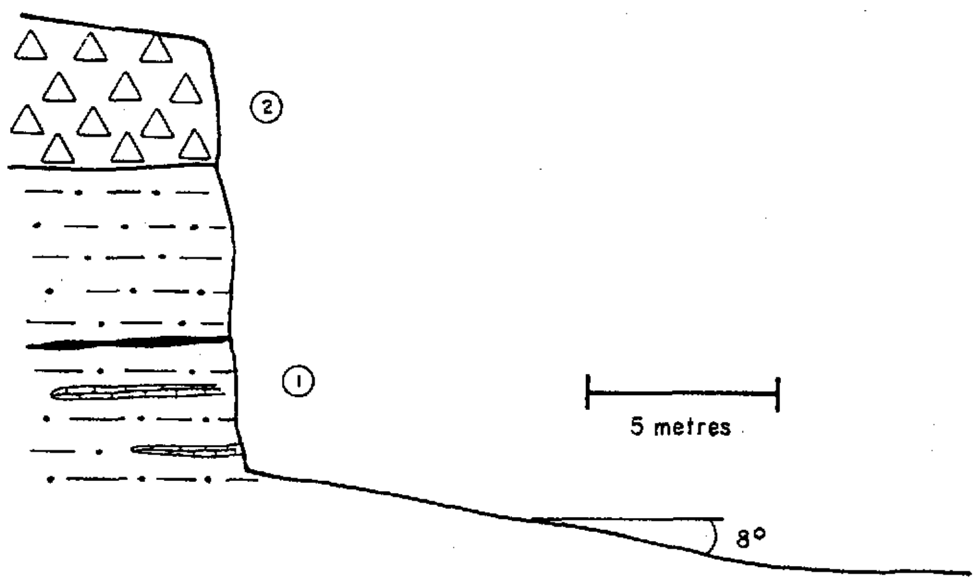
Wave Factors:

Effective Fetch:

Beach Riprap: CCC: 5%, scattered boulders,cobbles, and petrified wood.

Shoreline Geometry: West-facing bank along a point extending southward from a hilly dissected headland. Large shallow bay to the west.

Dominant Bank Failure Mechanisms: Toppling and high-angle sliding along large vertical bank-parallel fractures in the Upper Horseshoe Valley till extending down into the Sentinel Butte Formation.



<u>Figure 57</u>. Station 62.

APPENDIX III

BANK-FACE FRACTURE CHARACTERISTICS

EXPLANATION

Geologic Units
- oah - Oahe Formation
- uss - Upper Snow School till
- uhv - Upper Horseshoe Valley till
- umha - Upper Medicine Hill till
- umhb - Upper Medicine Hill till silt lenses
- sbms - Sentinel Butte Formation mudstone
- sbss - Sentinel Butte Formation Sandstone
- sbcr - Sentinel Butte Formation concretionary lenses

Fracture Trace Length Types
- Type X - both fracture ends visible
- Type Y - one fracture end visible
- Type Z - no fracture ends visible

Fracture Trace Geometry
- crv - curved
- str - straight
- irr - irregular

Fracture Surface Description
- sm - smooth
- rgh - rough
- mt - matte
- gyp - gypsum coated
- CaCO - calcium carbonate coating
- FeO - iron oxide coating
- cly - clay or mud coating

Width - fracture aperture width to the nearest millimetre

SENTINEL BUTTE FORMATION; LAKE SAKAKAWEA STATE PARK

unit	strike/dip	length (cm)	geometry	surface	width (mm)	unit	strike/dip	length (cm)	geometry	surface	width (mm)
sbms	270 90V	78X	st	m	2	sbms	104 87S	36X	cv	m	1
sbms	351 80E	79X	st	m	2	sbms	35 76W	152Y	cv	r	1
sbms	271 90V	51X	st	m	2	sbms	14 86W	38X	st	m	0
sbms	280 90V	23X	st	m	2	sbms	20 84W	43X	st	m	2
sbms	180 90V	23X	st	m	2	sbms	117 17N	63Y	cv	m	0
sbms	188 73NW	17X	st	m	3	sbms	18 84W	63X	st	m	0
sbms	266 78NW	84Y	st	m	1	sbms	104 85N	25X	st	m	0
sbms	269 65N	64Y	st	m	1	sbms	28 83W	13X	st	m	2
sbms	184 89W	64Y	st	m	--	sbms	9 85W	18X	st	m	0
sbms	165 80W	25Y	st	m	--	sbms	50 90V	30X	st	m	0
sbms	262 73N	140Y	st	--	--	sbms	52 90V	25X	st	m	0
sbms	263 74N	69X	st	--	--	sbms	9 65W	20X	st	m	0
sbms	263 86N	58X	st	--	--	sbms	24 83W	18X	st	m	0
sbms	175 85E	28Y	st	--	--	sbms	15 87W	102X	st	m	1
sbms	263 88S	20Y	st	--	--	sbms	175 84W	20X	st	m	2
sbms	193 86W	13X	--	--	--	sbms	63 50S	30X	st	m	0
sbms	274 78N	41X	--	--	--	sbms	180 73W	18X	st	m	0
sbms	160 76W	28X	--	--	--	sbms	77 80S	23X	st	m	0
sbms	275 78N	229Z	--	--	--	sbms	24 90V	18Y	st	m	0
sbms	245 86E	178Y	--	--	--	sbms	105 83N	36Y	st	m	0
sbms	194 90V	13X	--	--	--	sbms	19 80E	30X	st	m	1
sbms	195 81E	19X	--	--	--	sbms	98 87N	56X	st	m	3
sbms	272 79N	318Z	--	--	--	sbms	103 83S	28Y	st	r	2
sbms	173 87W	318Z	--	--	--	sbms	142 90V	127Y	st	m	6
sbms	275 80N	91X	--	--	--	sbms	86 --	--	--	--	--
sbms	264 77N	102X	--	--	--	sbms	174 --	--	--	--	--
sbms	184 83W	89X	--	--	--	sbms	172 --	--	--	--	--
sbms	178 81W	107X	--	--	--	sbms	180 --	--	--	--	--
sbms	156 86N	30X	st	m	2	sbms	178 --	--	--	--	--
sbms	110 90V	356X	zz	m	2	sbms	84 --	--	--	--	--
sbms	95 77N	89X	st	m	3	sbms	85 --	--	--	--	--
sbms	158 90V	152Y	cv,ir	r	4	sbms	95 --	--	--	--	--
sbms	153 71N	114X	st	m	2	sbms	176 --	--	--	--	--
sbms	104 81N	25X	st,ir	m	2	sbms	176 --	--	--	--	--
sbms	55 90V	38X	st	m	0	sbms	19 --	--	--	--	--
sbms	94 66N	127X	st	m	0	sbms	185 --	--	--	--	--
sbms	153 90V	38X	st	m	0	sbms	91 --	--	--	--	--
sbms	70 80N	23X	st	m	1	sbms	190 --	--	--	--	--
sbms	65 90V	76X	st	m	0	sbms	195 --	--	--	--	--
sbms	172 90V	--	st	m	--	sbms	35 --	--	--	--	--
sbms	79 90V	25X	st	m	0	sbms	95 --	--	--	--	--
sbms	106 77N	18X	st	m	0	sbms	89 --	--	--	--	--
sbms	36 86N	30X	st	m	0	sbms	50 --	--	--	--	--
sbms	55 90V	30X	st	m	3	sbms	131 --	--	--	--	--
sbms	138 78N	23Y	st	m	1	sbms	45 --	--	--	--	--
sbms	131 87N	81X	st	m	5	sbms	85 --	--	--	--	--
sbms	154 85N	114Y	st	m	4	sbms	105 --	--	--	--	--
sbms	105 81N	51X	st	m	2	sbms	115 --	--	--	--	--
sbms	110 87N	71X	st	m	2	sbms	180 --	--	--	--	--
sbss	30 87S	190Y	st	sm	0	sbms	120 --	--	--	--	--
sbss	145 90V	152Y	st,ir	r	6	sbms	94 --	--	--	--	--
sbss	18 81S	76X	st,ir	--	1	sbms	100 --	--	--	--	--
sbss	1 81E	114X	st	--	1	sbms	92 --	--	--	--	--
sbss	32 71N	127X	st	Fe	0	sbms	106 --	--	--	--	--
sbss	2 86E	102Y	st	gy	1	sbms	116 --	--	--	--	--
sbss	15 72W	51Y	cv	sm	2	sbms	150 --	--	--	--	--
sbss	10 90V	64Y	st	m	2	sbms	180 --	--	--	--	--
sbss	70 81S	25Z	st	sm	2	sbms	109 --	--	--	--	--
sbss	170 87W	203X	st	sm	2	sbms	89 --	--	--	--	--
sbss	20 70N	38X	st	sm,Fe	0	sbms	100 --	--	--	--	--

SENTINEL BUTTE FORMATION; LAKE SAKAKAWEA STATE PARK (Continued...)

unit	strike/dip		length (cm)	geometry	surface	width (mm)
sbss	38	75N	30X	st	sm	0
sbss	3	86E	51Y	st	r,gy	1
sbss	1	74E	89Y	st	sm,fe	3
sbss	53	87N	30X	st,ir	r	0
sbms	25	89S	46X	st	m	2
sbms	15	87W	56X	st	m	2
sbms	104	80N	64X	st	m	2
sbms	106	80N	127X	st	m	2
sbms	75	86S	30X	st	m	1
sbms	30	90V	102X	st	r	2
sbms	16	77W	28X	st	m	0
sbms	4	90V	36X	st	m	2
sbms	28	84W	127Y	st	m	2

unit	strike/dip		length (cm)	geometry	surface	width (mm)
sbms	114	--	--	--	--	--
sbms	105	--	--	--	--	--
sbms	105	--	--	--	--	--
sbms	180	--	--	--	--	--
sbms	100	--	--	--	--	--
sbms	145	--	--	--	--	--
sbms	90	--	--	--	--	--
sbms	40	--	--	--	--	--
sbms	36	--	--	--	--	--
sbms	180	--	--	--	--	--
sbms	110	--	--	--	--	--
sbms	162	--	--	--	--	--
sbms	88	--	--	--	--	--

SENTINEL BUTTE FORMATION; STATION 50

unit	strike/dip	length	geometry	surface	width
sbms	142 90V	88Z	st	--	0
sbms	202 80W	50Y	st	--	3
sbms	265 88N	35X	st	--	3
sbms	123 87SW	55X	st	--	0
sbms	137 88NE	25X	st	--	0
sbms	179 90V	38Z	st	--	0
sbms	130 90V	96Y	st	--	0
sbms	169 84E	99Y	st	--	12
sbms	204 87E	177X	st	--	3
sbms	170 78E	76Y	st	--	0
sbms	137 86SW	83Y	st	--	0
sbms	206 90V	58Z	st	--	0
sbms	168 90V	63Z	st	--	0
sbms	260 90V	30X	st	--	0
sbms	164 90V	36Z	st	--	0
sbms	161 90V	41Y	st	--	0
sbms	270 90V	42Y	st	--	0
sbms	265 90V	31Y	st	--	0
sbms	212 --	--	--	--	--
sbms	208 --	--	--	--	--
sbms	215 --	--	--	--	--
sbms	219 --	--	--	--	--
sbms	209 --	--	--	--	--
sbms	220 --	--	--	--	--
sbms	222 --	--	--	--	--
sbms	210 --	--	--	--	--
sbms	211 --	--	--	--	--
sbms	214 --	--	--	--	--
sbss	32 84NW	191X	st	m	3
sbss	32 90V	1016Z	st	m	6
sbss	24 81NW	279Y	st	m	0
sbss	30 90V	203X	st,ir	m	2
sbss	25 85SE	161Y	st	m	3
sbss	173 76W	114X	st	m	0
sbss	149 86SW	508X	st	r	2
sbss	170 88E	63X	st	m	2
sbss	85 86N	216Z	st	sm	0

unit	strike/dip	length	geometry	surface	width
sbss	31 85NW	76Y	st	m	0
sbss	12 81W	30Y	st	sm	1
sbss	177 79W	215X	cv	m	1
sbss	172 77W	254Y	st,ir	r	2
sbss	175 85W	254X	st	m	2
sbss	38 90V	381Z	cv,ir	r	3
sbss	40 90V	762Z	st	sm,Fe	0
sbss	160 84SW	1016Z	stir	r	2
sbss	40 81SE	317Y	stir	r	3
sbss	42 79SE	114X	cv,ir	r	1
sbss	31 88NW	190X	st,ir	r	1
sbss	51 77SE	1270Y	st	m	2
sbss	31 90V	254Z	st,ir	r	1
sbss	57 80NW	203Y	st	r	2
sbss	171 83W	178Y	st	r	0
sbss	43 87SE	178Z	st	r	0
sbss	8 90V	279Y	st,ir	r	3
sbss	9 83W	635Z	st	k	2
sbss	26 85NW	64Z	st	m	6
sbss	33 84NW	76Z	st	m	0
sbss	27 84NW	30X	st	m	0
sbss	32 83NW	140Z	st	m	0
sbss	37 79NW	46X	st	m	2
sbss	35 83NW	15X	st	m	0
sbss	30 81NW	23X	st	m	0
sbss	29 85SE	30X	st	m	0
sbss	35 81NW	25X	st	m	0
sbss	20 82NW	76Y	st	r	0
sbss	78 86SE	229Y	st	m	0
sbss	26 87NW	216Z	st	m	0
sbss	94 88N	203Y	st,ir	m	3
sbss	87 75N	89X	st,ir	r	1
sbss	180 80W	203Z	st	r	0
sbss	85 67N	140X	st	m	0
sbss	95 68N	178Z	st	m	0
sbss	55 90V	76Y	st	m	2
sbss	36 90V	20Y	st,ir	r	3

SENTINEL BUTTE FORMATION; FORT STEVENSON STATE PARK

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
sbss	136 90V	--	--	--	--	sbms	74 78S	51X	crv	r	2
sbss	140 90V	--	--	--	--	sbms	79 78S	64X	crv,ir	r	2
sbss	140 90V	--	--	--	--	sbms	105 72S	30X	st	sm	1
sbss	145 90V	--	--	--	--	sbms	143 85SW	38X	st	r	3
sbss	180 90V	--	--	--	--	sbms	93 90V	25X	crv	gy,Fe	--
sbss	86 90V	--	--	--	--	sbms	134 87SW	15X	st	ir,r	2
sbss	155 90V	--	--	--	--	sbms	140 88SW	23X	st	r	3
sbss	136 90V	--	--	--	--	sbms	9 77W	25X	st,ir	--	2
sbss	140 90V	--	--	--	--	sbms	98 69N	191X	st,ir	r	3
sbss	140 70NE	51Y	st	Fe	--	sbms	153 90V	25X	st,ir	r	3
sbss	104 85N	28X	st	--	0	sbms	92 75N	30Y	st	m	0
sbss	105 85N	76Y	st	m	2	sbms	171 83E	76X	st	gy,k	0
sbss	125 76NE	38X	st	m	2	sbms	172 75W	38Z	st	m	0
sbss	45 90V	51Y	st	m	2	sbms	100 90V	64Z	st	m	0
sbss	93 90V	36X	st	m	2	sbms	174 90V	76Y	st	m	3
sbss	78 82N	38X	st	--	2	sbms	90 90V	38Y	st,ir	r	3
sbss	145 87SW	30X	st	--	1	sbms	95 90V	114Y	cv,ir	r	4
sbss	94 86S	20X	st	--	1	sbms	35 64S	38X	st	gy	0
sbss	131 80SW	18X	st	m	2	sbms	13 80SE	127Y	st	cy	0
sbss	135 76SW	23X	st	m	2	sbms	9 74SE	152X	st	cy	2
sbss	92 85S	64Y	st	--	1	sbms	144 87SW	191Y	st	m	3
sbss	105 87S	51X	st	m	3	sbms	44 85NW	127X	st	m	3
sbss	104 88S	51Y	st	m,Fe	0	sbms	48 88SE	216Z	cv	--	0
sbss	50 86NW	15Y	st	m	0	sbms	95 90V	--	st	--	0
sbss	52 90V	25X	st	m	0	sbms	43 81SE	191Z	st	m	3
sbss	48 85NW	30Y	st	--	0	sbms	46 84SE	76X	st	m	2
sbss	86 90V	165Y	st	--	1	sbms	44 84SE	51X	st	m	1
sbss	140 75SW	23X	st	m,Fe	0	sbms	5 80SE	--	st	m	1
sbss	145 90V	38Y	st	m	0	sbms	51 84SE	44Y	st	m	2
sbss	138 85SW	15Y	st	m	0	sbms	55 66SE	114X	st	m	2
sbss	145 90V	25Y	st	m	0	sbms	175 83NE	--	st	--	0
sbss	45 86NW	20Y	st	m	0	sbms	45 90V	36X	st	r	3
sbss	140 90V	102X	st	m	2	sbms	88 83NW	41X	st	r	3
sbss	174 66W	64Y	st	--	0	sbms	173 76NE	38X	crv	--	0
sbss	10 85E	38X	st	--	0	sbms	55 85SE	36Y	st	--	0
sbss	45 90V	50Y	st	--	0	sbms	66 79SE	51X	st	--	0
sbss	12 78W	76Y	st	--	0	sbms	161 82NE	20X	st	--	1
sbss	41 86SE	71X	st	--	2	sbms	47 90V	64X	st	r	3
sbss	180 74W	64X	st	--	0	sbms	6 90V	30Z	st	r	0
sbss	50 77SE	51X	st	m	3	sbms	147 85N	254Z	st	r	0
sbms	85 76S	30X	st	r	3	sbms	85 88NW	51Z	st	r	0
sbms	75 84S	23X	st	m	0	sbms	35 80SE	152Y	st	r	2
sbms	95 84S	18X	st	m	0	sbms	55 86NW	30X	st,ir	r	3
sbms	90 57S	38X	st	m	2	sbms	20 82SE	114X	st	r	2
sbms	94 47S	25X	st	m	2	sbms	28 72SE	76X	st	r	3
sbms	115 50SW	38X	st	m	2	sbms	45 80SE	--	st	r	0
sbms	83 86N	20X	st	m	1	sbms	20 77SE	--	st	r	0
sbms	171 90V	38X	st	m	0	sbms	145 85SW	--	st	r	0
sbms	79 87N	28X	st	m	2	sbms	13 82SE	--	st	r	0
sbms	81 90V	114Z	st	m	3	sbms	136 79SW	--	st	r	0
sbms	144 85SW	48Z	st	--	0	sbms	290 83SW	114X	st	--	0
sbms	263 73N	43Y	st	--	0	sbms	200 78SW	89X	st	--	19
sbms	136 72SW	61Y	st	--	0	sbms	210 83SE	518X	st	--	6
sbms	162 45E	46X	st	--	0	sbms	215 83SE	28X	st	--	0
sbms	205 64SE	49X	st	--	0	sbms	220 71SE	33X	st	--	0
sbms	216 67NW	66Y	st	--	2	sbms	240 74SE	36X	st	--	0
sbms	147 86SW	30X	st	--	0	sbms	277 85S	51X	st	--	0
sbms	136 66NE	87Z	st	--	0	sbms	120 90V	76Y	st	--	3
sbms	186 84W	36Y	st	--	2	sbms	200 90V	445Z	st	--	0
sbms	189 90V	76Y	st	--	2	sbms	215 83SE	23X	st	--	0

SENTINEL BUTTE FORMATION; FORT STEVENSON STATE PARK (Continued...)

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
sbms	193 90V	56Y	st	--	3	sbms	224 78SE	13X	st	--	0
sbms	270 85N	51Y	st	--	0	sbms	170 80W	102X	st	--	0
sbms	280 85S	559Y	st	--	3	sbms	175 60W	76X	st	--	0
sbms	230 70SE	102X	st	--	0	sbms	180 87W	102X	st	--	0
sbms	290 82S	46X	st	--	2	sbms	140 78SW	30X	st	--	0
sbms	190 72W	33X	st	--	0	sbms	230 78SE	381Y	st	--	2
sbms	268 90V	41X	st	--	2	sbms	236 80SE	18Y	st	--	0
sbms	180 88W	109X	st	--	2	sbms	224 77SE	25X	st	--	0
sbms	120 85NE	23Y	st	--	0	sbms	178 75W	284X	st	--	2
sbms	136 84NE	330Z	st	--	2	sbss	250 90V	191Z	st	--	2
sbms	128 85NE	94Y	st	--	2	sbss	257 85NW	114X	st	--	0
sbms	230 52NW	160Y	st	--	0	sbss	155 90V	28X	st	--	0
sbms	267 87S	79X	st	--	2	sbss	155 90V	18X	st	--	0
sbms	160 90V	15X	st	--	0	sbss	125 86SE	8X	st	--	0
sbms	278 85S	15X	st	--	2	sbss	148 90V	13X	st	--	2
sbms	236 90V	30X	st	--	2	sbss	144 90V	36X	cv	--	0
sbms	150 23NW	58X	st	--	0	sbss	260 30N	30X	st	--	0
sbms	173 85W	343Y	st	--	3	sbss	280 77N	203Y	st	--	0
sbms	134 17NW	43X	st	--	3	sbss	192 77E	216Z	st	--	2
sbms	240 20NW	51X	st	--	3	sbss	130 82SW	97Y	st	--	2
sbms	130 40NW	102Y	st	--	0	sbss	138 80SW	178Y	st	--	0
sbms	268 89S	53X	st,ir	--	3	sbss	120 77SW	114X	st	--	0
sbms	274 80S	48Y	st	--	3	sbss	185 63W	28X	st	--	0
sbms	180 80E	81Z	st	--	0	sbss	240 90V	127Z	st	--	0
sbms	196 90V	178Y	cv	--	6	sbss	215 90V	38X	st	--	0
sbms	220 87SE	43X	st	--	0	sbss	225 25NW	20X	zz	--	0
sbms	274 85S	109Y	st	--	0	sbss	218 90V	81X	st	--	0
sbms	204 73S	122X	st	--	0	sbss	190 85W	18Y	st	--	0
sbms	240 90V	178Y	st	--	0	sbss	181 73W	102X	st	--	0
sbms	287 86S	445Z	st	--	0	sbss	185 90V	8Y	st	--	0
sbms	190 86E	36Y	st	--	0	sbss	185 90V	8X	st	--	0
sbms	296 60N	53X	cv	--	0	sbss	188 90V	10X	st	--	0
sbms	149 83SW	160Z	st	--	2	sbss	230 85SE	51Y	st	--	0
sbms	151 76SW	61Y	st	--	6	sbss	235 73SE	23X	st	--	0
sbms	240 85SE	381Z	st	--	2	sbss	245 63NW	18Y	zz	--	2
sbms	210 80SE	48X	st	--	3	sbss	255 81NW	28Y	st	--	0
sbms	275 66SE	18X	st	--	0	sbss	130 76SW	254Z	st	--	2
sbms	255 80SE	13X	st	--	0	sbss	240 78SE	46X	st	--	2
sbms	142 90V	36X	st	--	0	sbss	204 90V	33X	st	--	0
sbms	280 84SE	15X	st	--	0	sbss	290 73S	28Y	st	--	2

SENTINEL BUTTE FORMATION; STATIONS 60, 61, AND 62

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
sbms	320 87E	20Z	st	--	0	sbcr	169 --	--	--	--	--
sbms	318 79W	10Z	st	--	0	sbcr	93 --	--	--	--	--
sbms	315 78E	8X	st	--	0	sbcr	94 --	--	--	--	--
sbms	325 90V	18Y	st	--	0	sbcr	91 --	--	--	--	--
sbms	225 75N	15Y	st	--	0	sbcr	37 --	--	--	--	--
sbms	226 82N	20Y	st	--	0	sbcr	90 --	--	--	--	--
sbms	316 84E	13Y	st	--	0	sbcr	5 --	--	--	--	--
sbms	227 90V	15Y	st	--	0	sbcr	91 --	--	--	--	--
sbms	314 90V	8Z	st	--	0	sbcr	2 --	--	--	--	--
sbms	260 90V	71Y	st	--	0	sbcr	82 --	--	--	--	--
sbms	253 75N	43X	st	--	0	sbcr	172 --	--	--	--	--
sbms	355 90V	46X	st	--	0	sbcr	140 --	--	--	--	--
sbms	216 90V	38X	st	--	0	sbcr	111 --	--	--	--	--
sbms	245 87S	41X	st	--	0	sbcr	100 --	--	--	--	--
sbms	270 78N	69X	st	--	0	sbcr	145 --	--	--	--	--
sbms	190 84E	10X	st	--	0	sbcr	150 --	--	--	--	--
sbms	271 80N	13X	st	--	0	sbcr	33 --	--	--	--	--
sbms	270 80N	13X	st	--	1	sbcr	90 --	--	--	--	--
sbms	256 90V	18X	st	--	1	sbcr	91 --	--	--	--	--
sbms	177 87E	15X	st	--	0	sbcr	94 --	--	--	--	--
sbms	272 80N	15X	st	--	1	sbcr	85 --	--	--	--	--
sbms	305 86W	89Y	st	--	0	sbcr	89 --	--	--	--	--
sbms	340 90V	13X	st	--	0	sbcr	105 --	--	--	--	--
sbms	256 77N	23Y	st	--	0	sbcr	111 --	--	--	--	--
sbms	266 76N	30Y	cv	--	0	sbcr	118 --	--	--	--	--
sbms	262 90V	13Y	st	--	0	sbcr	142 --	--	--	--	--
sbms	180 90V	36Y	st	--	0	sbcr	143 --	--	--	--	--
sbcr	84 --	--	--	--	--	sbcr	132 --	--	--	--	--
sbcr	171 --	--	--	--	--	sbcr	22 --	--	--	--	--
sbcr	18 --	--	--	--	--	sbms	89 58	20	st,ir	r	2
sbcr	132 --	--	--	--	--	sbms	85 75	23	st,ir	r	2
sbcr	66 --	--	--	--	--	sbms	75 83	20	st,ir	r	3
sbcr	82 --	--	--	--	--	sbms	131 88	33	st	m	2
sbcr	172 --	--	--	--	--	sbms	77 81	20	st	sm	1
sbcr	15 --	--	--	--	--	sbms	80 58	15	st	--	0
sbcr	27 --	--	--	--	--	sbms	31 85	28	st	--	0
sbcr	78 --	--	--	--	--	sbms	145 78	23	st	--	0
sbcr	81 --	--	--	--	--	sbms	109 89	20	st	m	1
sbcr	145 --	--	--	--	--	sbms	104 86	25	st	m	1
sbcr	23 --	--	--	--	--	sbms	98 86	18	st	m	3
sbcr	111 --	--	--	--	--	sbms	41 88	15	st	m	2
sbcr	163 --	--	--	--	--	sbms	45 89	15	st,ir	r	2
sbcr	145 --	--	--	--	--	sbms	89 79	30	st	r	0
sbcr	90 --	--	--	--	--	sbms	141 85	25	st	r	0
sbcr	17 --	--	--	--	--	sbms	39 88	38	st	r	2
sbcr	85 --	--	--	--	--	sbms	115 83	38	st	r	1
sbcr	90 --	--	--	--	--	sbms	97 88	15	st	m	0
sbcr	104 --	--	--	--	--	sbms	138 84	18	st	--	1
sbcr	170 --	--	--	--	--	sbms	115 80	30	st	m	0
sbcr	50 --	--	--	--	--	sbms	39 85	25	st	m	0
sbcr	35 --	--	--	--	--	sbms	47 87	38	st	m	0
sbcr	82 --	--	--	--	--	sbms	146 81	28	st	m	0
sbcr	162 --	--	--	--	--	sbcr	10 --	--	--	--	--
sbcr	115 --	--	--	--	--	sbcr	175 --	--	--	--	--
sbcr	135 --	--	--	--	--	sbcr	183 --	--	--	--	--
sbcr	45 --	--	--	--	--	sbcr	4 --	--	--	--	--
sbcr	45 --	--	--	--	--	sbcr	5 --	--	--	--	--
sbcr	48 --	--	--	--	--	sbcr	15 --	--	--	--	--
sbcr	120 --	--	--	--	--	sbcr	12 --	--	--	--	--
sbcr	145 --	--	--	--	--	sbcr	20 --	--	--	--	--

SENTINEL BUTTE FORMATION; STATIONS 60, 61, AND 62 (Continued...)

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
sbcr	96 --	--	--	--	--	sbcr	10 --	--	--	--	--
sbcr	50 --	--	--	--	--	sbcr	175 --	--	--	--	--
sbcr	155 --	--	--	--	--	sbcr	174 --	--	--	--	--
sbcr	146 --	--	--	--	--	sbcr	177 --	--	--	--	--
sbcr	87 --	--	--	--	--	sbcr	182 --	--	--	--	--
sbcr	84 --	--	--	--	--	sbcr	5 --	--	--	--	--
sbcr	172 --	--	--	--	--	sbcr	104 --	--	--	--	--
sbcr	175 --	--	--	--	--	sbcr	102 --	--	--	--	--
sbcr	82 --	--	--	--	--	sbcr	98 --	--	--	--	--
sbcr	15 --	--	--	--	--	sbcr	101 --	--	--	--	--
sbcr	15 --	--	--	--	--	sbcr	86 --	--	--	--	--
sbcr	103 --	--	--	--	--	sbcr	95 --	--	--	--	--
sbcr	100 --	--	--	--	--	sbcr	43 --	--	--	--	--
sbcr	101 --	--	--	--	--	sbcr	142 --	--	--	--	--
sbcr	170 --	--	--	--	--	sbcr	47 --	--	--	--	--
sbcr	90 --	--	--	--	--	sbcr	40 --	--	--	--	--
sbcr	90 --	--	--	--	--	sbcr	178 --	--	--	--	--
sbcr	93 --	--	--	--	--	sbcr	2 --	--	--	--	--

UPPER MEDICINE HILL TILL; STATION 51

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
umha	270 75S	64X	st	Fe,gy	0	umha	50 90V	20Z	st	gy	0
umha	130 68NE	18X	cv	Fe,gy	0	umha	115 85N	191Z	st	gy	0
umha	145 74NE	8X	st	Fe	0	umha	190 90V	25Z	st	gy	0
umha	258 90V	109Y	st	Fe,gy	2	umha	100 78NE	33X	st,ir	r,Fe	0
umha	185 85W	33X	cv	Fe,gy	0	umha	30 73NW	13X	st	Fe	0
umha	147 51NE	28X	st	Fe	0	umha	156 78SW	18X	st	Fe	0
umha	145 55NE	18X	st	--	0	umha	7 82NW	10X	st	Fe	0
umha	202 72NW	46X	cv	Fe	0	umha	71 86NW	30X	st	Fe	0
umha	204 62NW	38X	st	Fe,gy	0	umha	53 86SE	23X	st	Fe	0
umha	166 72W	33X	st	Fe,gy	0	umha	120 64NE	8X	st	Fe	0
umha	164 78W	43X	st	Fe,gy	0	umha	25 71SE	10X	st	Fe	0
umha	154 74W	36X	st	Fe,gy	0	umha	62 88NW	36X	st,ir	gy	0
umha	166 78W	109X	st	Fe,gy	0	umha	70 79NW	25X	st,ir	Fe,gy	0
umha	189 73W	36X	st	Fe	0	umha	37 79SE	51X	st,ir	Fe,gy	0
umha	195 75W	38X	st	Fe	0	umha	36 75SE	13X	st	Fe	0
umha	186 86W	158Y	st	Fe,gy	0	umha	55 78SE	122X	st	Fe	0
umha	150 90V	127Y	st	Fe,gy	0	umha	152 49NW	38X	cv	Fe	0
umha	144 84NE	99Y	st	Fe,gy	0	umha	84 88NW	64X	cv,ir	Fe	0
umha	205 81W	114X	st	Fe	0	umha	102 81NE	18X	st	Fe	0
umha	194 75W	69X	st	Fe	0	umha	88 79SE	38X	st	Fe	0
umha	206 78W	119Z	st	Fe	0	umha	73 79SE	89X	st,ir	Fe	0
umha	190 79W	40X	st	Fe	0	umha	130 66NE	30X	st	Fe	0
umha	197 78W	28X	st	Fe,gy	0	umha	5 64NW	25X	cv	Fe	0
umha	175 21E	44X	st	Fe,gy	0	umha	142 90V	20X	st	Fe	0
umha	198 21N	28X	st	Fe	0	umha	73 77SE	10X	st	Fe	0
umha	137 26NE	138X	st	Fe	0	umha	174 43SW	25X	st	Fe	0
umha	239 57NW	203X	cv	Fe	0	umha	143 32SE	25X	st	Fe	0
umha	291 43NW	152X	cv	Fe,gy	0	umha	16 45NW	23X	st	Fe	0
umha	256 22NW	101X	cv	Fe,gy	0	umha	80 87SE	--	st	Fe	0
umha	131 90V	101Y	st	gy	3	umha	96 39NE	38X	cv	sm,Fe	0
umha	90 75S	76X	st	Fe	0	umha	10 68NW	18X	st	Fe	0
umha	81 79S	38X	st	Fe	0	umha	98 79SW	152Z	st,ir	r,Fe	1
umha	180 90V	25X	st	Fe	0	umha	128 76NE	64X	st	Fe	0
umha	135 78SW	30X	st	Fe	0	umha	178 75SW	20X	st	Fe	0
umha	160 90V	20X	st	Fe	1	umha	5 71NW	25X	cv	Fe	0
umha	105 90V	191Z	st	m	6	umha	172 47SW	20X	st	Fe	0
umha	100 80N	20X	st	Fe,gy	0	umha	155 45SW	15X	st	Fe	0
umha	190 90V	191Z	cv	m	6	umha	165 90V	18X	cv	Fe	0
umha	195 90V	229Z	st,ir	Fe	3	umha	4 54NW	20X	st	Fe	0
umha	185 90V	102Y	st	Fe	2	umha	149 90V	30X	st	Fe	0
umha	200 90V	76X	cv	m	3	umha	48 80SE	--	st	Fe	0
umha	110 78S	38X	st	Fe	0	umha	178 64SW	13X	st	Fe	0
umha	130 82SW	127Y	st	Fe	0	umha	5 70SE	30X	st	Fe	0
umha	110 85S	152Y	st	gy	0	umha	9 60SE	18X	st	Fe	0
umha	150 80S	102Y	st	gy	0	umha	20 10NW	51X	cv	Fe	0
umha	183 30NW	15X	st	sm	0	umha	163 87NE	13X	st	Fe	0
umha	194 90V	18X	st	Fe	0	umha	205 60NW	46X	cv	r,Fe	0
umha	154 70NE	33X	st	Fe	0	umha	166 82NE	41X	st	r,Fe	0

UPPER MEDICINE HILL TILL; STATION 53

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
umha	270 76N	43X	cv	--	0	umha	45 86SE	13X	st	--	0
umha	210 75S	10X	st	--	2	umha	82 60N	38X	cv	Fe	0
umha	127 90V	102Y	st,ir	--	3	umha	45 82SE	28X	st,ir	r	1
umha	162 68E	23X	st,ir	--	0	umha	90 84S	23Z	st	m	0
umha	270 74N	36X	st	--	0	umha	134 84NE	20X	st	Fe	0
umha	175 65W	43X	st,ir	--	0	umha	180 90V	36X	cv	Fe	0
umha	265 82N	15X	st	--	0	umha	155 80NE	25Y	st	--	0
umha	163 79E	28Y	cv,ir	--	0	umha	145 76N	25Y	st	--	0
umha	180 75W	18X	st	--	0	umha	1 59W	38Y	st	--	0
umha	177 84W	86X	st	--	0	umha	160 57W	36X	st	Fe	0
umha	271 89S	419Y	st	--	1	umha	7 90V	25Y	cv	Fe	0
umha	280 70S	140Y	st	--	2	umha	158 66SW	38X	st	Fe	0
umha	171 65S	38Z	st	--	0	umha	157 90V	18X	cv	r,Fe	0
umha	292 75N	10X	st	--	0	umha	145 90V	15X	st	Fe	0
umha	230 73NW	132Y	st	--	6	umha	140 63SW	15X	st	Fe	0
umha	142 61SW	43X	cv	--	2	umha	177 75W	38X	cv,ir	r,Fe	0
umha	134 65SW	36Y	cv	k	0	umha	149 82SW	64Y	stir	r,Fe	0
umha	265 84N	432Z	st	gy	2	umha	151 90V	36X	st	Fe	0
umha	166 90V	25X	st	Fe	0	umha	9 90V	43Y	stir	r	0
umha	160 60W	10X	st	gy	0	umha	5 87W	36X	st	Fe	0
umha	170 82W	28Z	st	gy,Fe	0	umha	157 72W	30X	st	sm,Fe	0
umha	262 16S	97X	st	--	1	umha	80 82NW	20X	st	--	0
umha	166 24NW	101X	st	--	2	umha	85 90V	20X	st,ir	r	0
umha	175 36NW	15X	st	--	1	umha	110 10SW	38X	cv,ir	r,Fe	0
umha	164 88W	23X	st	gy,Fe	0	umha	85 84NW	89X	st,ir	gy,k	0
umha	270 85N	84X	st	--	0	umha	170 14SW	41X	cv,ir	gy,k	0
umha	88 78N	36X	st	r,Fe	0	umha	173 84SW	23X	st,ir	r,Fe	0
umha	43 70SW	23X	st,ir	r,Fe	0	umha	125 80SW	51X	st,ir	Fe,gy	0
umha	84 64S	25X	st,ir	r,Fe	0	umha	138 77SW	23X	st	Fe	0
umha	81 54N	20X	st,ir	r,Fe	0	umha	100 80SW	25X	st,ir	m	2
umha	148 63SW	25X	st	r,Fe	0	umha	115 85NE	38X	st,ir	gy,k	3
umha	85 90V	30X	st,ir	r,Fe	0	umha	129 72SW	25X	st,ir	m,Fe	0
umha	5 85W	28X	st,ir	r,gy	0	umha	28 79SE	28Y	st	r,Fe	0
umha	95 90V	38X	st	m	0	umha	88 78SE	36X	st	r,Fe	1
umha	15 90V	152Y	cv,ir	r,Fe	0	umha	100 90V	330Z	st	r	0
umha	70 87SE	102Y	st,ir	r	0	umha	161 69NE	102X	st	--	0
umha	150 86NE	38X	st	r,Fe	0	umha	170 80SW	30X	st	--	0
umha	98 84S	20X	st	--	0	umha	74 78NW	28X	st,ir	r	1
umha	60 83SE	20X	st	sm,Fe	0	umha	65 70NW	18X	st,ir	m	2
umha	110 90V	25X	cv	gy	0	umha	85 81SW	15X	st,ir	m	0
umha	140 90V	20X	st	--	0	umha	73 78SW	23X	st,ir	m	0
umha	31 81SE	97X	st	r,gy	2	umha	170 90V	41X	st,ir	m	0
umha	29 66SE	36X	st	r,gy	0	umha	85 81SW	30X	st	r	0
umha	32 72SE	43X	cv,ir	gy,k	3	umha	78 90V	140Y	st	r	2
umha	148 87SW	76X	st,ir	m	1	umha	106 16SW	25X	cv	gy	0
umha	121 73SW	23X	st	r,Fe	0	umha	40 5SE	191X	st	Fe,gy	0
umha	29 68SE	25X	st	r,Fe	0	umha	129 18SW	71X	st	gy	0

UPPER MEDICINE HILL TILL; STATIONS 58 AND 59

unit	strike/dip	length	geometry	surface	width
umhb	194 61E	127Y	st	--	0
umhb	125 90V	38Y	cv,ir	r	25
umhb	180 59E	106X	st	--	0
umhb	238 58NW	8X	st	--	0
umhb	234 85SE	28X	st	--	0
umhb	204 85SE	8X	st	--	0
umhb	224 48NW	13X	st	--	0
umhb	222 71SE	30X	st	--	0
umhb	256 78SE	13X	st	--	0
umhb	229 90V	18X	st	--	0
umhb	220 90V	58Y	st	--	0
umhb	270 90V	140Y	cv	--	1
umhb	203 88SE	33X	st	--	0
umhb	145 76SW	46Y	st	m	0
umhb	154 85SW	25X	st	--	0
umhb	255 85SE	87Z	st	m	0
umhb	199 74N	23Y	st	--	0
umhb	202 78N	76Y	st	m	0
umhb	256 74NW	69Y	st	r	2
umhb	206 70NW	94Y	st	--	0
umhb	212 78NW	25X	st	--	1
umhb	256 72SE	140X	st	--	1
umhb	250 78SE	76Y	st	r	2
umhb	260 75SE	76X	st	--	1
umhb	255 83SE	23X	st	--	0
umha	163 90V	10X	st,ir	--	0
umha	245 90V	20X	st	Fe,gy	0
umha	191 90V	5X	st	--	0
umha	166 81W	33Y	st	Fe,gy	2
umha	287 90V	28Z	st	--	0
umha	228 83SE	25Z	st	Fe	0
umha	135 90V	30Y	st,ir	--	2
umha	206 86SE	15Y	st	--	0
umha	180 74E	28Y	st	m	1
umha	114 90V	23Y	st	m	0
umha	230 69SE	33X	st	Fe	0
umha	225 73SE	15X	st	--	0
umha	220 83SE	36X	st	Fe	0
umha	117 81NE	28X	st	--	0
umha	177 83E	13X	st	--	0
umha	157 76NE	33X	st	--	0
umha	272 72NW	13X	st	--	0
umha	119 46SW	13X	cv	Fe	0
umha	193 20E	89Y	cv	r	2
umha	189 20E	41X	cv	--	0
umha	222 30NW	30X	cv	Fe	0
umha	233 26SE	15X	cv	Fe	0
umha	120 90V	102X	st	--	1
umha	225 90V	25X	cv	--	0
umha	170 53S	13X	cv	--	0
umha	230 75NW	10X	st	--	0
umha	278 86N	101X	st	--	1
umha	177 78W	46X	cv	r	3
umha	181 80W	445Y	st	--	3
umha	250 85SE	305Y	st	--	2
umha	137 73NE	20X	st	--	0
umha	178 72E	89X	st	--	0

unit	strike/dip	length	geometry	surface	width
umha	225 90V	20X	st	--	2
umha	260 78N	64Y	cv	--	0
umha	288 76N	36X	st	--	0
umha	132 79SW	28Y	st	--	0
umha	154 85NE	15X	st	--	0
umha	161 84NE	13X	st	--	0
umha	128 60SW	33X	st	--	0
umha	136 73SW	25X	st	--	0
umha	145 70SW	10X	st	--	0
umha	154 84NE	18X	st	--	1
umha	135 56SW	15X	st	--	0
umha	140 40NE	43X	st	--	0
umha	150 58NE	36Y	st	--	0
umha	135 70SW	20Y	st	--	0
umha	130 62SW	23X	st	--	0
umha	132 37SW	28X	st	--	0
umha	82 90V	38X	st	m	0
umha	155 90V	38X	st,ir	r	0
umha	45 52SE	56X	st	--	0
umha	80 35SE	76X	st	m	0
umha	85 70N	15X	st	m	0
umha	105 70N	30Y	st	--	0
umha	45 83NW	20Y	st,ir	r	0
umha	104 90V	23X	st,ir	r	0
umha	144 90V	20X	st	Fe	0
umha	83 63S	43X	st,ir	Fe,gy	0
umha	136 69NE	41X	st	sm,Fe	0
umha	145 64NE	89X	st	Fe	0
umha	135 64NE	127X	st,ir	r,Fe	0
umha	95 78N	46X	st	r	0
umha	115 82NE	25X	st	--	0
umha	145 84NE	15X	st	sm,Fe	0
umha	143 70NE	25X	st	--	0
umha	77 42NW	76X	st,ir	Fe,gy	0
umha	105 75N	33X	st	m	0
umha	127 83NE	36X	st,ir	--	0
umha	19 61E	76Y	st	--	0
umha	99 79N	18X	st	Fe	0
umha	70 74SE	64Y	cv,ir	--	0
umha	36 55SE	--	st	r	0
umha	131 82NE	25Y	cv	--	0
umha	107 70N	13Y	cv	--	0
umha	98 81N	15X	cv	--	0
umha	85 83S	18Y	st	--	0
umha	82 85S	28Y	st	--	0
umha	100 64N	8X	st	Fe	0
umha	40 73SE	203X	cv,ir	r	3
umha	55 76SE	76X	st	r,Fe	0
umha	70 80SE	64X	cv,ir	Fe,gy	0
umha	88 48S	102X	st	gy,k	0
umha	80 82S	25X	st	gy,Fe	0
umha	70 87SE	30X	st,ir	r,k	0
umha	48 90V	25X	st,ir	r,k	0
umha	35 70SE	102X	st,ir	r,k	0
umha	175 75W	76X	st	--	0
umha	41 82SE	64X	st	--	0
umha	82 61N	25X	st	Fe	0

UPPER HORSESHOE VALLEY TILL; STATIONS 51 AND 52

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
uhv	200 90V	305Y	st	r	1	uhv	240 40NW	12X	st	--	1
uhv	204 90V	28X	st	--	0	uhv	194 41SE	28X	st	--	2
uhv	140 90V	635Z	st,ir	r	6	uhv	195 34SE	26X	st	r	3
uhv	190 90V	203X	cv,ir	r	1	uhv	200 32NW	13X	st	r	3
uhv	189 90V	27.94X	st	--	0	uhv	25 79NW	76Y	st,ir	m	6
uhv	186 89E	17Y	st,ir	Fe,gy	3	uhv	100 90V	38X	st,ir	r	3
uhv	124 90V	41X	st	r	2	uhv	122 87NE	89Y	st,ir	r	2
uhv	190 90V	48Y	st	Fe,gy	0	uhv	131 84NE	114Y	st	m	0
uhv	204 90V	51Y	st	r	1	uhv	82 84NW	127X	st,ir	r	3
uhv	122 90V	572Y	st,ir	--	2	uhv	142 90V	216Y	st	r	3
uhv	177 67W	46X	st	r	2	uhv	117 90V	216Y	st	r	2
uhv	210 71NW	89X	st	r	0	uhv	141 85SW	33X	st	r	2
uhv	161 90V	43X	cv	r	2	uhv	1 84W	229Y	st,ir	gy,Fe	3
uhv	215 80NW	102Y	cv,ir	r	16	uhv	152 86SW	114Y	st	r	3
uhv	203 90V	94X	st	--	1	uhv	148 83SW	38X	st,ir	r	0
uhv	195 74W	76Z	st	--	0	uhv	165 88W	191X	st,ir	m	3
uhv	224 90V	64Y	st	r	2	uhv	155 87NE	76X	st,ir	r	2
uhv	197 85W	89X	st	r	2	uhv	15 90V	635Z	st,ir	r,cy	4
uhv	210 90V	41X	st	--	1	uhv	3 86W	762Z	st	r,gy,k	2
uhv	212 90V	109Y	st	r,gy	2	uhv	64 86SE	56X	st	r	1
uhv	250 90V	445Z	st,ir	r	19	uhv	65 90V	330Z	st,ir	r,cy	6
uhv	135 90V	107X	st	--	0	uhv	57 90V	76X	st	m	0
uhv	130 90V	127X	st,ir	--	0	uhv	95 90V	25X	st	m	0
uhv	211 90V	89Z	st	r	0	uhv	105 90V	38X	st	m	0
uhv	114 90V	41X	st	--	0	uhv	18 67SE	114Y	st	r	0
uhv	130 90V	356Y	st,ir	--	0	uhv	174 70E	38X	st	r	0
uhv	260 90V	20X	st	--	0	uhv	150 79NE	76X	st,ir	r	1
uhv	231 90V	46X	st	--	0	uhv	160 90V	25X	st,ir	r	0
uhv	112 90V	191Y	st	--	0	uhv	139 90V	254X	st,ir	r	1
uhv	115 90V	140X	st	--	0	uhv	149 70SW	203Y	st,ir	r	0
uhv	225 90V	66X	st	--	1	uhv	25 90V	165Z	cv,ir	r	2
uhv	134 90V	163Y	st	--	6	uhv	22 83SE	140Y	st	r	2
uhv	217 90V	102Z	st	r	3	uhv	145 90V	127X	st	MnO	0
uhv	186 90V	33X	st	--	0	uhv	131 81SW	89X	st	r	1
uhv	213 86NW	292Z	st	r	1	uhv	145 85SW	76X	st,ir	MnO	2
uhv	145 90V	51X	cv	--	2	uhv	10 84W	127X	st	r	2
uhv	219 84NE	158Y	st	--	0	uhv	13 82E	76X	st	m.	0
uhv	217 86NE	137Z	st	r	2	uhv	5 84E	89X	st	r	0
uhv	225 90V	76X	st	--	0	uhv	22 86E	165Y	st,ir	r	2
uhv	213 68NW	66X	st	--	0	uhv	34 84E	64X	st,ir	m	2
uhv	290 64N	76Y	st,ir	--	0	uhv	138 90V	127Y	st	r	0
uhv	225 90V	61X	st	--	0	uhv	170 90V	127Y	st	m	0
uhv	212 82NW	48Y	st	--	0	uhv	85 90V	89Y	st	m	0
uhv	240 90V	63Y	st	r	3	uhv	60 90V	51X	st	r	3
uhv	157 16NE	40X	st,ir	gy,Fe	10	uhv	100 80S	33X	st	r	2
uhv	160 15NE	9X	st	Fe	0	uhv	135 90V	25Y	st	m,Fe	0
uhv	146 40SW	21Y	st	r	3	uhv	80 90V	38Y	st	m	0
uhv	75 90V	25Y	st	m	0	uhv	85 90V	30Y	st	m	0

UPPER HORSESHOE VALLEY TILL; STATION 60

unit	strike/dip	length	geometry	surface	width
uhv	320 90V	122Y	st	--	2
uhv	20 90V	36Y	st	--	2
uhv	335 90V	41Y	st	--	0
uhv	350 84W	66Y	cv	--	1
uhv	335 61W	43X	st	--	0
uhv	310 74E	140Z	st	--	1
uhv	340 78W	76Y	st	--	2
uhv	319 73E	28X	st	--	0
uhv	338 84W	64Y	st	--	1
uhv	358 75W	140Z	st	k	2
uhv	290 90V	140Y	st.	--	2
uhv	326 67W	76Y	st	--	2
uhv	285 90V	36X	st	--	2
uhv	338 76W	43X	cv	--	1
uhv	305 90V	33X	st	--	0
uhv	280 90V	140Y	st	--	1
uhv	326 90V	152Z	st	--	2
uhv	327 86W	178Y	st	--	2
uhv	335 90V	102X	cv	--	2
uhv	240 90V	91X	st	--	2
uhv	335 87E	254Z	st	--	2
uhv	15 79SE	25X	st	r	1
uhv	175 80SW	28X	st	r	1
uhv	31 88SE	127Y	st	r	3
uhv	54 86SE	102X	st,ir	r	2
uhv	133 85NE	114Y	st	r	6
uhv	150 86NE	33X	st	r	3
uhv	145 87NE	--	st	r	0

unit	strike/dip	length	geometry	surface	width
uhv	146 84SW	76Y	st	r	0
uhv	150 64SW	381Y	st	r	3
uhv	44 90V	127Y	st	r	3
uhv	3 90V	508Z	st	r	6
uhv	147 67SW	89X	st,ir	r	6
uhv	172 90V	33X	st,ir	r	0
uhv	45 85SE	38X	st,ir	r	0
uhv	35 80NW	30Y	st	r	0
uhv	19 79NW	25X	st	r	0
uhv	19 78NW	191Y	st	r,gy	2
uhv	175 25NE	33X	ir	r	2
uhv	36 87NW	51Y	st	r	0
uhv	141 80SW	76Y	st	r	3
uhv	46 79NW	25X	st	r	0
uhv	171 86SW	178X	cv	r	1
uhv	34 74NW	51X	st	r	0
uhv	49 79NW	114X	st,ir	r	3
uhv	45 75NW	51Y	st	r	2
uhv	144 68SW	36X	st	r	3
uhv	147 75SW	64Y	st	r	2
uhv	43 87NW	38Z	st	r	0
uhv	165 83SW	114Y	st	r	0
uhv	8 86NW	203Y	st	r	6
uhv	31 90V	46Y	st	r	2
uhv	168 78SW	51X	st	r	1
uhv	33 78NW	48X	st	r	0
uhv	2 90V	51X	st	r	3

UPPER SNOW SCHOOL TILL; STATIONS 6 AND 7

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
uss	230 78E	43Y	st	--	9	uss	166 90V	13X	st	--	0
uss	160 90V	20Y	--	--	1	uss	274 79S	76Y	--	--	0
uss	284 88N	61X	cv	--	3	uss	105 75S	81Y	st	--	0
uss	316 76N	36Y	st	--	2	uss	275 88S	69Y	st	--	0
uss	230 78E	43Y	st	--	1	uss	155 82W	58Y	st	--	3
uss	195 78E	99Z	st	--	1	uss	140 89SW	114Z	st	--	6
uss	260 35S	81X	st	--	1	uss	265 83S	18X	st	--	1
uss	268 90V	15Z	st	--	0	uss	273 87S	13X	st	--	2
uss	180 83W	43X	st	--	0	uss	258 86S	15X	st	--	2
uss	195 87E	20Z	st	--	2	uss	260 75S	23X	st	--	2
uss	188 81S	38X	st	--	0	uss	140 82SW	140Z	st	--	0
uss	196 85W	33X	st	--	1	uss	265 88S	64Y	st	--	0
uss	190 89E	20X	st	--	0	uss	137 89NE	76Y	st	mt	0
uss	178 89E	13X	st	--	0	uss	54 75SE	38Y	st	mt	0
uss	195 90V	18X	st	--	0	uss	57 77SE	25X	st	mt	0
uss	227 90V	25X	st	--	0	uss	20 90V	20X	st	mt	0
uss	110 90V	13X	st	--	0	uss	174 80SW	30X	st	r	0
uss	190 87W	64X	st	--	0	uss	25 78SE	36X	st,ir	r	0
uss	109 89W	64X	st	--	3	uss	5 84NW	25X	st,ir	r	0
uss	215 84E	10X	st	--	0	uss	145 87SW	28X	st,ir	mt	0
uss	115 90V	18Y	st	--	0	uss	45 77SE	13X	st	mt	0
uss	204 90V	36Z	st	--	0	uss	171 81SW	23X	st,ir	r	0
uss	135 87S	22Z	st	--	2	uss	84 82NW	64Z	cv,ir	r	3
uss	180 73W	13X	st	--	0	uss	81 90V	18Y	cv	sm	0
uss	185 90V	28Y	st	--	0	uss	175 88SW	114Y	st	mt	2
uss	250 80SW	20Y	st	--	0	uss	140 73SW	25X	st	mt	0
uss	245 77SW	10Y	st	--	0	uss	63 80SE	28X	cv,ir	r	0
uss	247 81SW	15Y	st	--	0	uss	16 81SE	12X	cv,ir	r	0
uss	171 85W	33X	st	--	1	uss	35 79SE	20X	st	mt	0
uss	195 85W	25X	st	--	0	uss	108 84SW	114Y	st,ir	r	2
uss	265 87N	58X	st	--	1	uss	20 90V	36X	st	mt	0
uss	190 72E	20X	st	--	0	uss	12 86SE	46Y	st	mt	0
uss	104 57S	43Y	st	--	0	uss	138 85SW	12X	st,ir	mt	0
uss	185 85N	64X	st	--	0	uss	40 90V	18X	cv,ir	r	0
uss	161 88W	38Y	st	--	0	uss	28 76SW	318Z	st	mt	2
uss	169 88E	41Y	st	--	0	uss	155 86SW	28X	st,ir	mt	0
uss	204 90V	76Y	st	--	0	uss	134 84SW	23X	st	mt	0
uss	209 90V	89Z	st	--	12	uss	95 86N	76X	st,ir	r	0
uss	199 90V	46X	st	--	0	uss	143 74NE	18X	cv	r	0
uss	203 85E	58X	st	--	0	uss	152 63NE	28X	st	r	0
uss	157 90V	91Y	st	--	0	uss	100 90V	25X	st,ir	r	0
uss	171 88W	102Z	st	--	2	uss	135 90V	25X	st	mt	0
uss	214 90V	36X	st	--	0	uss	127 87NE	38X	st	mt	0
uss	216 90V	41X	st	--	0	uss	76 84NW	44X	st	mt	0
uss	235 85N	64Y	st	--	0	uss	70 75SE	76Y	cv	--	0
uss	263 90V	33X	st	--	1	uss	70 80SE	51X	st	--	0
uss	257 85S	89Y	st	--	3	uss	48 90V	25X	st	--	0
uss	199 78W	46Y	st	--	1	uss	79 80SE	36X	st	--	0
uss	225 85E	58X	st	--	0	uss	38 90V	12Y	cv	--	0
uss	270 90V	114Y	cv	--	2	uss	15 75SE	89X	cv	--	2
uss	199 90V	114X	st	--	0	uss	15 90V	64Y	st	--	1
uss	220 90V	76Y	st	--	2	uss	41 83NW	76X	st,ir	--	0
uss	240 90V	25Z	st	--	0	uss	55 83SE	51Y	st	--	0
uss	255 90V	127Z	st	--	12	uss	88 77NW	64Y	st,ir	--	0
uss	193 90V	61Y	st	--	0	uss	82 90V	46X	st,ir	--	0
uss	197 90V	178Z	st	--	1	uss	95 85N	12Z	cv,ir	--	3
uss	256 89N	84Y	st	--	3	uss	96 85N	20X	st	--	0
uss	261 89N	102Y	st	--	0	uss	65 80NW	12X	st	mt	2
uss	110 90V	89Z	st	--	0	uss	100 90V	89X	cv,ir	--	3
uss	102 90V	38X	st	--	1	uss	81 90V	114Y	cv	--	3
uss	235 70S	38X	cv	--	2	uss	76 83NW	36X	st	sm	1

UPPER SNOW SCHOOL TILL; STATIONS 6 AND 7 (Continued...)

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
uss	200 90V	25X	cv	--	1	uss	180 75W	20X	st,ir	mt	0
uss	210 84E	23X	st	--	0	uss	30 84SE	38X	st	--	1
uss	168 89W	102X	st	--	0	uss	210 80SE	323Z	--	--	0
uss	130 73W	114Y	st	--	0	uss	120 24NE	28X	st	--	0
uss	14 13SE	18X	st	--	0	uss	70 12NW	10X	st	--	3
uss	230 78E	43Y	st	--	9	uss	166 90V	13X	st	--	0

UPPER SNOW SCHOOL TILL; STATIONS 6 AND 7

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
uss	209 74W	25X	cv	--	0	uss	168 80W	76X	st,r	cy	1
uss	215 76W	20X	st	--	0	uss	29 78NW	15X	st	r	0
uss	104 90V	101Y	st	--	0	uss	165 78NE	30X	st,ir	r	2
uss	189 86W	165Y	st	--	18	uss	124 78SW	12X	st	r,cy	0
uss	328 90V	152Y	st	--	30	uss	152 72SW	35X	st	r,cy	0
uss	303 89NE	139X	st	--	3	uss	95 51N	20X	st	r,cy	0
uss	250 86N	12X	st	--	0	uss	135 80SW	50X	st,ir	r,cy	2
uss	232 89NW	279Y	st	--	12	uss	47 87NW	50Y	st	m	0
uss	305 68NE	25X	st	--	0	uss	166 84W	279Y	st	sm	2
uss	260 90V	88X	st	--	0	uss	178 88W	45Y	st	m	0
uss	291 90V	60Z	st	--	0	uss	168 87W	38X	st	r,cy	2
uss	293 86N	38X	st	--	0	uss	112 62SW	12X	st	r,Fe	0
uss	312 90V	152X	cv	--	0	uss	145 85SW	63X	st	m	2
uss	270 90V	292Z	st	--	3	uss	165 86SW	20Y	st	r	1
uss	300 85N	114Y	st	--	3	uss	40 65SE	30X	st	r,Fe	0
uss	285 84N	101Y	st	--	6	uss	144 90V	50Z	st	m,Fe	0
uss	207 71NW	25X	st	--	0	uss	70 70SE	12X	st	m	0
uss	180 85W	177Y	st	--	0	uss	105 75NE	25X	st	m	0
uss	268 90V	50X	st	--	0	uss	107 75NE	20X	st	m	0
uss	200 90V	15X	st	--	0	uss	162 64NE	88X	st,ir	m	0
uss	182 83W	38X	st	--	0	uss	135 78NE	17X	st	r	0
uss	199 60W	43X	st	--	0	uss	70 90V	114Y	st,ir	r,gy	2
uss	155 42SW	254Y	st	--	0	uss	108 88SW	20X	st	m,Fe	0
uss	174 81E	144X	st	--	1	uss	134 89SW	20X	st	m,Fe	0
uss	185 90V	25X	st	--	0	uss	63 81SE	25X	st	m,Fe	0
uss	148 40SW	101X	st	--	0	uss	5 71E	22X	st	m,Fe	0
uss	194 59W	35X	st	--	0	uss	135 60NE	76X	st,ir	r,Fe	0
uss	274 79S	33Y	st	--	1	uss	41 88SE	63X	cv,ir	r,Fe	0
uss	297 87S	71Y	st	--	1	uss	135 80NE	101X	st	m,Fe	0
uss	202 70W	40X	st	--	3	uss	160 75NE	63X	st	m,Fe	0
uss	165 88W	152Y	st	--	1	uss	80 85SE	20X	st	m,Fe	0
uss	145 90V	139X	st	--	1	uss	125 65SW	25X	cv	m,Fe	0
uss	161 78W	22X	st	--	0	uss	90 88N	38X	st	m,Fe	0
uss	100 78S	25X	cv	--	0	uss	70 85SE	25X	st	m,Fe	0
uss	133 83SW	55X	st	--	1	uss	175 52NE	15X	st	m,Fe	0
uss	125 70SW	45X	st	--	1	uss	170 60NE	7X	st	sm,Fe	0
uss	137 58SW	165X	cv	--	1	uss	160 69NE	20X	st	m,Fe	0
uss	104 40N	8X	cv	--	0	uss	162 83NE	25X	st	ir,r	0
uss	129 9SW	30X	st	--	0	uss	95 90V	15X	st	m	0
uss	163 16NE	8X	st	--	0	uss	110 80NE	25X	st	m	0
uss	151 86SW	63X	st	m	1	uss	165 82SW	101Z	st	r	0
uss	160 21NE	8X	st	--	0	uss	171 20NE	13X	st	--	1

OAHE FORMATION, LAKE SAKAKAWEA STATE PARK

unit	strike/dip	length	geometry	surface	width	unit	strike/dip	length	geometry	surface	width
oah	240 84S	53Z	st	--	3	oah	68 --	--	--	--	--
oah	160 90V	58Z	st	--	6	oah	48 --	--	--	--	--
oah	210 90V	58Z	st	--	3	oah	77 --	--	--	--	--
oah	274 88S	28Y	st	--	0	oah	15 --	--	--	--	--
oah	187 78E	15Y	st	--	0	oah	24 --	--	--	--	--
oah	187 77E	14X	st	--	2	oah	31 --	--	--	--	--
oah	210 87NW	58Z	st	--	3	oah	165 --	--	--	--	--
oah	195 87E	46Y	st	--	2	oah	0 --	--	--	--	--
oah	196 88E	48Z	st	--	1	oah	4 --	--	--	--	--
oah	160 90V	74Z	st	--	2	oah	72 --	--	--	--	--
oah	225 88SE	66Y	st	--	0	oah	66 --	--	--	--	--
oah	238 89SE	46Y	st	--	0	oah	178 --	--	--	--	--
oah	126 88NE	30Y	st	--	0	oah	32 --	--	--	--	--
oah	160 90V	53Z	st	--	0	oah	17 --	--	--	--	--
oah	230 90V	53Z	st	--	0	oah	107 --	--	--	--	--
oah	155 90V	36Y	st	--	0	oah	90 --	--	--	--	--
oah	135 90V	20Y	st	--	0	oah	145 --	--	--	--	--
oah	123 83SW	38Y	st	--	0	oah	3 --	--	--	--	--
oah	225 90V	48Z	st	--	0	oah	167 --	--	--	--	--
oah	202 90V	48Z	st	--	0	oah	135 --	--	--	--	--
oah	134 90V	48Z	st	--	0	oah	25 --	--	--	--	--
oah	195 90V	56Z	st	--	0	oah	2 --	--	--	--	--
oah	227 90V	25Y	st	--	0	oah	124 --	--	--	--	--
oah	215 90V	15Z	st	--	1	oah	19 --	--	--	--	--
oah	257 88S	36Z	st	--	0	oah	63 --	--	--	--	--
oah	267 89S	43Z	st	--	0	oah	2 --	--	--	--	--
oah	117 90V	36Y	st	--	0	oah	11 --	--	--	--	--
oah	234 90V	41Y	st	--	0	oah	55 --	--	--	--	--
oah	265 84S	15Z	st	--	3	oah	92 --	--	--	--	--
oah	140 90V	41Y	st	--	0	oah	148 --	--	--	--	--
oah	195 90V	23Y	st	--	0	oah	159 --	--	--	--	--
oah	154 90V	38Y	st	--	1	oah	42 --	--	--	--	--
oah	220 90V	38Y	st	--	1	oah	154 --	--	--	--	--
oah	165 90V	25X	st	--	1	oah	133 --	--	--	--	--
oah	180 90V	18Y	st	--	0	oah	171 --	--	--	--	--
oah	195 90V	25Z	st	--	0	oah	143 --	--	--	--	--
oah	110 90V	13X	st	--	0	oah	152 --	--	--	--	--
oah	130 90V	41Z	st	--	0	oah	153 --	--	--	--	--
oah	250 90V	41Z	st	--	2	oah	170 --	--	--	--	--
oah	55 --	--	--	--	--	oah	63 --	--	--	--	--
oah	55 --	--	--	--	--	oah	165 --	--	--	--	--
oah	52 --	--	--	--	--	oah	162 --	--	--	--	--
oah	71 --	--	--	--	--	oah	70 --	--	--	--	--
oah	165 --	--	--	--	--	oah	40 --	--	--	--	--
oah	17 --	--	--	--	--	oah	75 --	--	--	--	--
oah	3 --	--	--	--	--	oah	62 --	--	--	--	--
oah	33 --	--	--	--	--	oah	77 --	--	--	--	--
oah	55 --	--	--	--	--	oah	85 --	--	--	--	--
oah	45 --	--	--	--	--	oah	62 --	--	--	--	--
oah	55 --	--	--	--	--	oah	101 --	--	--	--	--
oah	23 --	--	--	--	--	oah	95 --	--	--	--	--
oah	17 --	--	--	--	--	oah	90 --	--	--	--	--
oah	70 --	--	--	--	--	oah	82 --	--	--	--	--

OAHE FORMATION, STATION 52

unit	stike/dip		length	geometry	surface	width
oha	85	--	--	--	--	--
oha	115	--	--	--	--	--
oha	131	--	--	--	--	--
oha	156	--	--	--	--	--
oha	98	--	--	--	--	--
oha	85	--	--	--	--	--
oha	48	--	--	--	--	--
oha	135	--	--	--	--	--
oha	160	--	--	--	--	--
oha	133	--	--	--	--	--
oha	115	--	--	--	--	--
oha	35	--	--	--	--	--
oha	55	--	--	--	--	--
oha	133	--	--	--	--	--
oha	136	--	--	--	--	--
oha	110	--	--	--	--	--
oha	77	--	--	--	--	--
oha	128	--	--	--	--	--
oha	54	--	--	--	--	--
oha	103	--	--	--	--	--
oha	77	--	--	--	--	--
oha	95	--	--	--	--	--
oha	4	--	--	--	--	--
oha	137	--	--	--	--	--
oha	75	--	--	--	--	--

unit	stike/dip		length	geometry	surface	width
oha	122	--	--	--	--	--
oha	144	--	--	--	--	--
oha	35	--	--	--	--	--
oha	49	--	--	--	--	--
oha	155	--	--	--	--	--
oha	135	--	--	--	--	--
oha	88	--	--	--	--	--
oha	145	--	--	--	--	--
oha	119	--	--	--	--	--
oha	177	--	--	--	--	--
oha	92	--	--	--	--	--
oha	85	--	--	--	--	--
oha	92	--	--	--	--	--
oha	131	--	--	--	--	--
oha	120	--	--	--	--	--
oha	162	--	--	--	--	--
oha	104	--	--	--	--	--
oha	6	--	--	--	--	--
oha	2	--	--	--	--	--
oha	7	--	--	--	--	--
oha	140	--	--	--	--	--
oha	14	--	--	--	--	--
oha	172	--	--	--	--	--
oha	169	--	--	--	--	--
oha	169	--	--	--	--	--

APPENDIX IV

BANK-TOP FRACTURE CHARACTERISTICS

EXPLANATION

Headings

Station - Bank recession station number.

Pin# - Measuring pin number to indicate location. Not listed for fractures measured along bank-parallel transects.

Position - Distance from bank edge in metres.

Width - Fracture aperture width in centimetres.

Length - Fracture length in metres.

Orientation - Fracture orientation degrees from north.
- bp = approximate bank-parallel orientation
- p = approximate bank-perpendicular

Lithology - underlying geologic unit.

Underlying Geologic Unit

oah - Oahe Formation
uss - Upper Snow School till
uhv - Upper Horseshoe Valley till
umh - Upper Medicine Hill till
sbms - Sentinel Butte Formation mudstone

Bank-Top Fractures

Station	Pin#	Position	Width	Length	Orientation	Lithology
1	8	0.74	2	2.5	149	oah
2	1	0.79	0	0.6	165	sbms
2	1	0.90	9	15.0	140	sbms
2	2	1.12	1	0.5	130	sbms
2	2	1.66	1	3.0	135	sbms
2	3	0.86	1	7.0	138	sbms
2	3	1.80	2	15.0	134	sbms
2	4	1.50	10	15.0	134	sbms
3	5	0.70	8	2.0	095	oah
4	2	0.24	3	3.0	235	uss
4	3	1.60	2	1.5	225	uss
5	2	0.49	3	2.5	040	uss
7	1	0.86	6	9.0	063	uss
7	1	---	--	8.0	130	uss
7	2	0.97	1	0.5	110	uss
50	2	0.75	--	--	bp	sbms
50	4	0.74	2	4.0	035 bp	sbms
51	1	0.86	1	1.4	090 bp	uhv
51	1	1.43	5	9.0	bp	uhv
51	1	2.23	2	17.0	bp	uhv
51	2	0.21	3	17.0	bp	uhv
51	2	2.77	3	5.0	105 bp	uhv
51	3	0.29	2	2.0	bp	uhv
51	3	2.96	2	9.0	bp	uhv
51	5	3.80	3	3.5	109 bp	uhv
51	5	1.92	1	2.6	bp	uhv
51	6	2.03	18	9.0	bp	uhv
51	6	3.28	2	5.0	107 bp	uhv
51	7	1.34	2	1.5	108 bp	uhv
51	7	2.87	2	0.5	108 bp	uhv
51	8	0.73	4	1.1	030	uhv
51	8	1.36	21	8.0	070 bp	uhv
51	10	0.91	9	3.5	060 bp	uhv
51	--	1.0	1	7.0	174	uhv
51	--	1.0	2	3.0	163	uhv
51	--	1.0	2	0.4	040	uhv
51	--	1.0	2	1.5	025	uhv
51	--	1.0	2	3.0	034	uhv
51	--	3.0	0	2.0	058	uhv
51	--	3.0	1	4.0	180	uhv
51	--	3.0	1	1.7	006	uhv
51	--	3.0	0	1.5	170	uhv
51	--	3.0	0	1.3	012	uhv
51	--	3.0	1	2.5	135	uhv
51	--	3.0	1	1.5	045	uhv
51	--	3.0	0	1.0	042	uhv
51	--	3.0	0	0.4	015	uhv
51	--	5.0	1	0.8	160	uhv
51	--	5.0	0	2.0	160	uhv
52	1	0.59	1	1.3	195 bp	uhv
52	1	1.11	1	0.4	-- bp	uhv
52	2	1.10	2	2.2	170 bp	uhv
52	2	1.90	2	3.0	-- bp	uhv
52	3	1.06	12	14.0	194 bp	uhv
52	5	0.26	5	4.0	-- bp	uhv
52	5	0.46	2	2.2	-- bp	uhv
52	5	1.37	2	10.0	187 bp	uhv
52	6	0.81	2	10.0	187 bp	uhv

Bank-Top Fractures

Station	Pin#	Position	Width	Length	Orientation	Lithology
52	6	1.79	1	1.5	187 bp	uhv
52	7	1.08	2	12.0	028 bp	uhv
52	8	0.54	7	11.0	022 bp	uhv
52	8	1.55	7	12.0	028 bp	uhv
52	--	1.00	1	0.2	-- p	uhv
52	--	1.00	2	1.1	-- p	uhv
52	--	3.00	1	0.5	-- p	uhv
53	1	1.35	2	--	-- bp	umh
53	7	0.25	1	--	-- bp	umh
53	9	1.37	1	--	-- bp	umh
53	--	1.00	0	0.3	227	umh
53	--	3.00	0	0.8	258	umh
53	--	5.00	0	0.7	207	umh
54	--	3.00	1	0.4	219	sbms
54	--	8.00	1	0.2	220	sbms
56	1	1.29	2	--	-- bp	uss
56	1	2.30	5	--	-- bp	uss
56	3	0.74	4	--	-- bp	uss
56	3	1.69	3	--	-- bp	uss
56	2	5.00	0	0.4	282	uss
57	1	0.35	6	--	-- bp	uss
57	1	1.34	5	--	-- bp	uss
57	2	1.12	2	--	-- bp	uss
57	4	0.50	10	--	-- bp	uss
57	6	0.73	1	--	-- bp	uss
57	6	1.37	1	--	-- bp	uss
57	7	1.05	3	--	-- bp	uss
57	7	1.73	4	--	-- bp	uss
57	8	1.05	3	--	-- bp	uss
57	8	1.91	5	--	-- bp	uss
57	--	1.00	4	1.0	180	uss
58	5	1.58	1	8.0	250 bp	umh
58	7	0.78	3	4.5	145 bp	umh
58	3	1.00	3	1.0	235	umh
58	4	1.00	1	2.5	180	umh
58	5	1.00	1	0.5	205	umh
58	6	8.00	1	1.2	030	umh
59	4	1.36	1	6.0	115 bp	umh
59	4	1.00	2	1.7	074	umh
59	3	1.00	3	2.0	180	umh
59	3	3.00	1	0.3	155	umh
59	2	1.00	2	2.0	145	umh
59	2	1.00	1	0.5	160	umh
60	1	0.98	4	4.0	160 bp	uss
61	1	0.38	2	3.0	220 bp	uss
61	1	2.67	1	1.0	225 bp	uss
61	5	0.99	1	4.0	090 bp	uss
62	3	1.96	1	0.5	-- bp	uss
62	5	0.52	4	4.0	165 bp	uss
62	4	1.00	1	0.5	200	uss
62	4	1.00	1	0.5	254	uss

APPENDIX V

HORIZONTAL FRACTURE FREQUENCY

EXPLANATION

Headings

Unit/Station	geologic unit and station number
Orientation	transect orientation (degrees from north)
Length	transect length in metres
Number	number of fractures counted along transect
Frequency	number of fractures intersected per metre

Geologic Units

oah	Oahe Formation
uss	Upper Snow School till
uhv	Upper Horseshoe Valley till
umh	Upper Medicine Hill till
sbms	Sentinel Butte Formation mudstone
sbss	Sentinel Butte Formation sandstone
sblg	Sentinel Butte Formation lignite

Horizontal Fracture Frequency

Unit/Station	Orientation	Length	Number	Frequency
uss 1	149	5.00	9	1.80
uss 3	080	13.00	8	0.62
uss 4	245	5.40	14	2.60
uss 5	225	10.00	9	0.90
uss 5	235	5.00	9	1.80
uss 5	180	8.00	5	0.63
uss 6/7	175	10.50	21	2.00
uss 6/7	242	4.50	17	3.80
uhv 60	185	8.25	9	1.10
uhv 60	245	5.25	2	0.38
umh 51	272	7.00	49	7.00
umh 51	231	4.00	48	12.00
umh 53	143	8.00	41	5.10
umh 53	195	3.00	9	3.00
umh 58	298	4.50	31	6.90
umh 58	110	3.75	19	5.10
umhs 58	110	10.50		0.86
umhs 58	258	6.00	2	2.00
umh 59	275	8.25	26	3.20
umh 59	240	4.50	20	4.40
uhv 51	258	23.00	19	0.83
uhv 52	205	17.00	18	1.06
uhv 52	160	9.00	4	0.44
oah 1	149	5.00	10	2.00
oah 3	080	5.50	14	2.50
oah 4	245	5.00	21	4.20
sbms 2	140	5.00	44	8.80
sblg 50	235	2.00	46	23.00
sbss 50	235	15.00	46	3.10
sbms 53	282	4.00	18	4.50
sbms 54/55	147	8.00	32	4.00
sbms 54/55	290	1.00	4	4.00
sbms 54/55	153	2.00	10	5.00
sblg 60	185	3.75	55	15.70
sbss 56	---	9.00	11	1.22
sbss 57	154	6.75	8	1.90
sbms 57	132	5.25	19	3.60

APPENDIX VI

VERTICAL FRACTURE FREQUENCY

EXPLANATION

Headings

- Unit/Station- geologic unit and station number
- Orientation - transect orientation (degrees from north)
- Length - transect length in metres
- Number - number of fractures counted along transect
- Frequency - number of fractures intersected per metre

Geologic Units

- oah - Oahe Formation
- uss - Upper Snow School till
- uhv - Upper Horseshoe Valley till
- umh - Upper Medicine Hill till
- sbms - Sentinel Butte Formation mudstone
- sbss - Sentinel Butte Formation sandstone
- sblg - Sentinel Butte Formation lignite

Vertical Fracture Frequency

Unit/Station	Orientation	Length	Number	Frequency
uss 1	149	15.0	48	3.2
uss 3	080	12.0	30	2.5
uss 3	105	8.0	32	4.0
uss 4	245	15.0	64	4.3
uss 4	290	6.0	31	5.2
uss 6/7	175	11.0	32	2.9
uss 6/7	128	5.0	5	1.0
uss 6/7	---	7.0	17	2.4
uss 6/7	242	7.0	19	2.7
uss 5	225	5.0	19	3.8
uss 5	235	6.0	26	4.3
uss 5	180	6.0	26	4.3
uss 60	185	9.0	23	2.6
uhv 51	258	15.0	30	2.0
umh 51	272	5.0	25	5.0
umh 51	231	4.0	23	5.8
uhv 52	205	13.5	38	2.8
uhv 52	160	8.0	20	2.5
umh 53	143	5.0	8	1.6
umh 53	195	2.5	11	4.4
umhs 58	110	8.5	24	2.8
umh 58	258	3.0	25	8.3
umh 58	110	6.0	45	7.5
umhs 58	258	7.0	13	1.9
umh 59	275	10.0	55	5.5
umh 59	240	4.0	29	7.3
sbms 2	140	12.5	50	4.2
sbss 50	235	15.0	29	1.93
sblg 50	235	2.0	46	23
sbms 53	282	6.0	28	4.7
sbms 54/55	147	12.0	50	4.2
sbms 54/55	290	1.0	5	5.0
sbms 54/55	153	5.0	25	5.0
sbms 56	140	12.0	61	5.0
sbss 57	147	5.0	8	1.6
oah 1	149	15.0	120	8.0
oah 3	080	5.0	50	10.0
oah 4	245	7.5	73	9.7

APPENDIX VII

VERTICAL FRACTURE LENGTH DISTRIBUTIONS

EXPLANATION

Type X - fracture lengths with both ends visible

Type Y - fracture lengths with one end visible

Type Z - fracture lengths with no ends visible

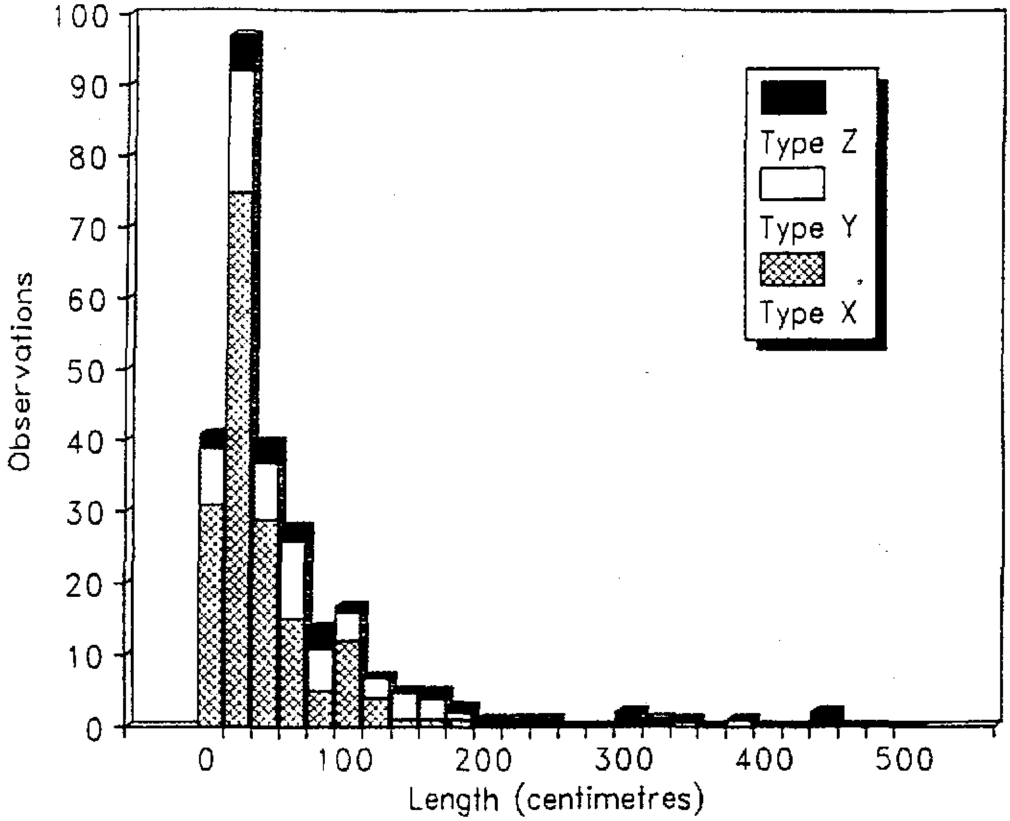
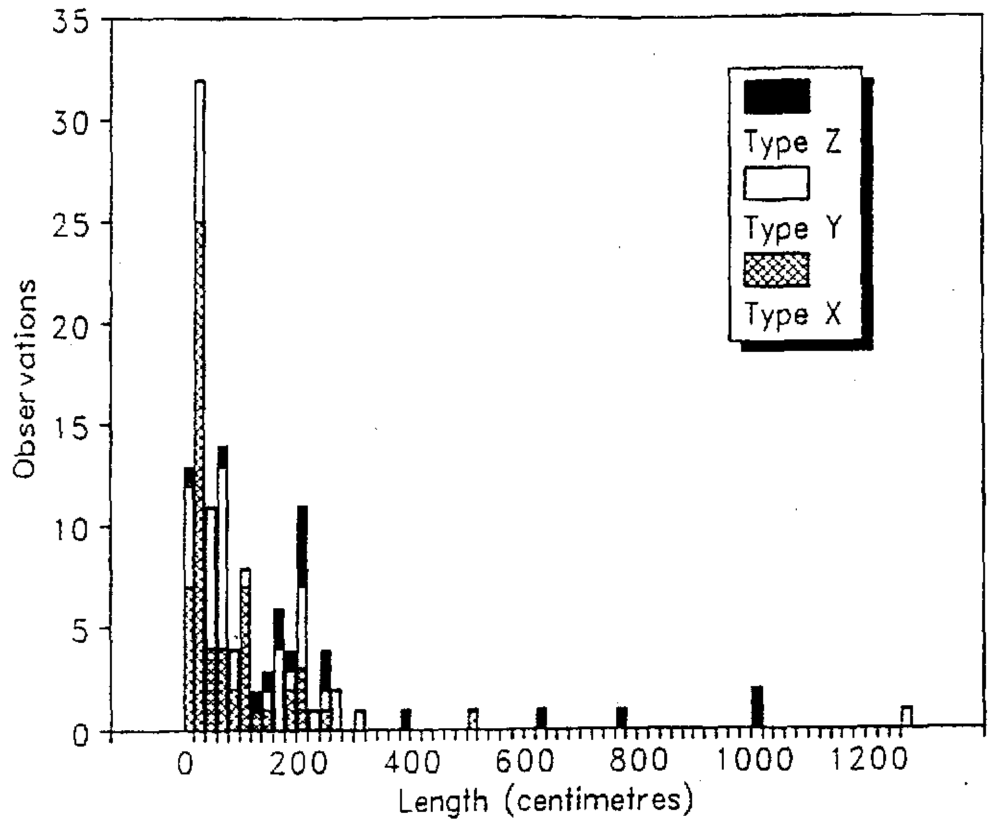
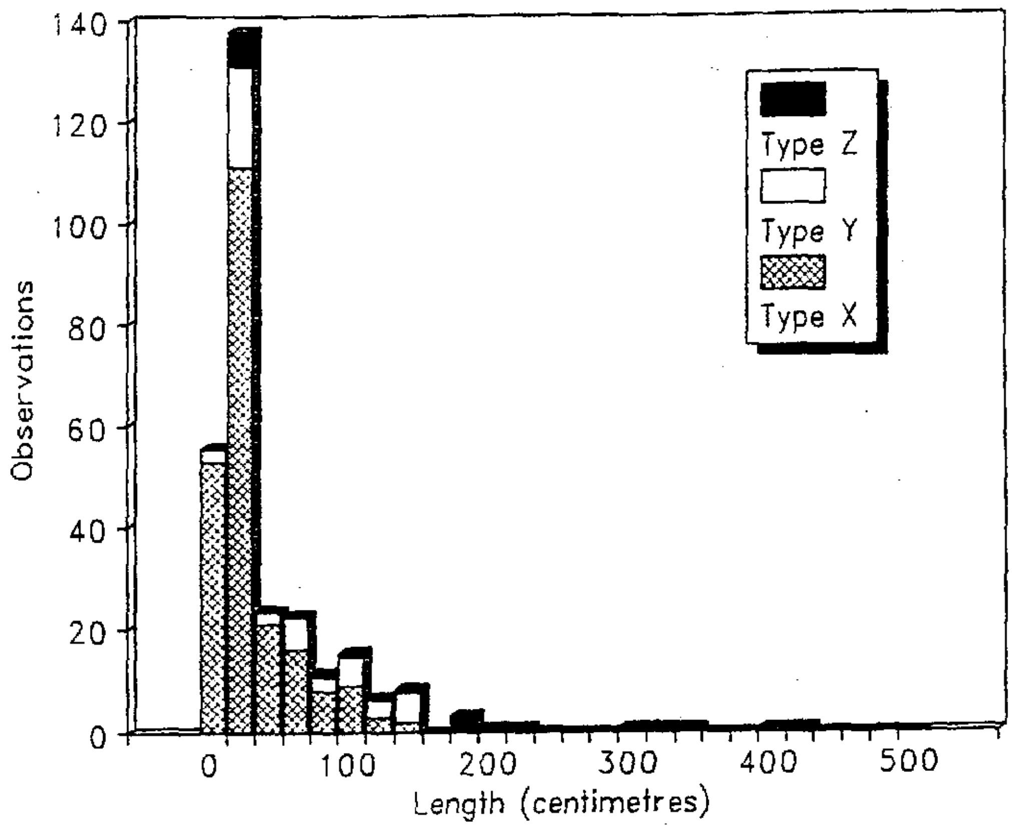


Figure 58. Vertical Fracture Length Distribution, Sentinel Butte Formation Mudstone.



<u>Figure 59</u>. Vertical Fracture Length Distribution, Sentinel Butte Formation Sandstone.



<u>Figure 60</u>. Vertical Fracture Length Distribution, Upper Medicine Hill Till.

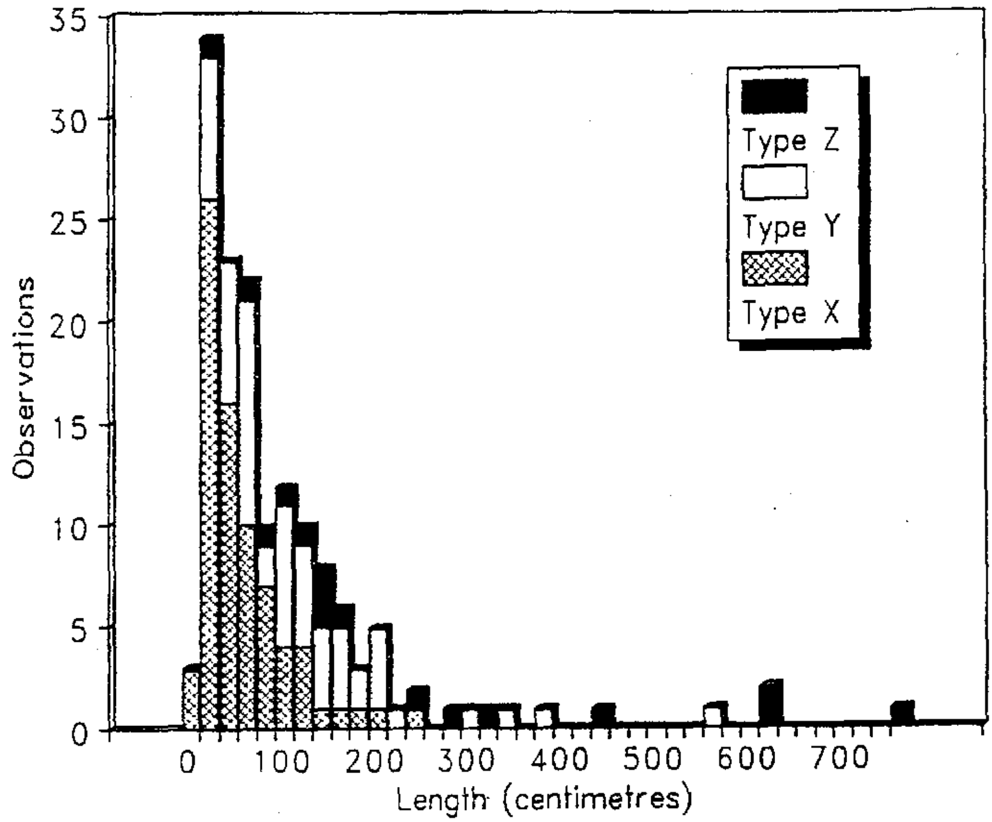


Figure 61. Vertical Fracture Length Distribution, Upper Horseshoe Valley Till.

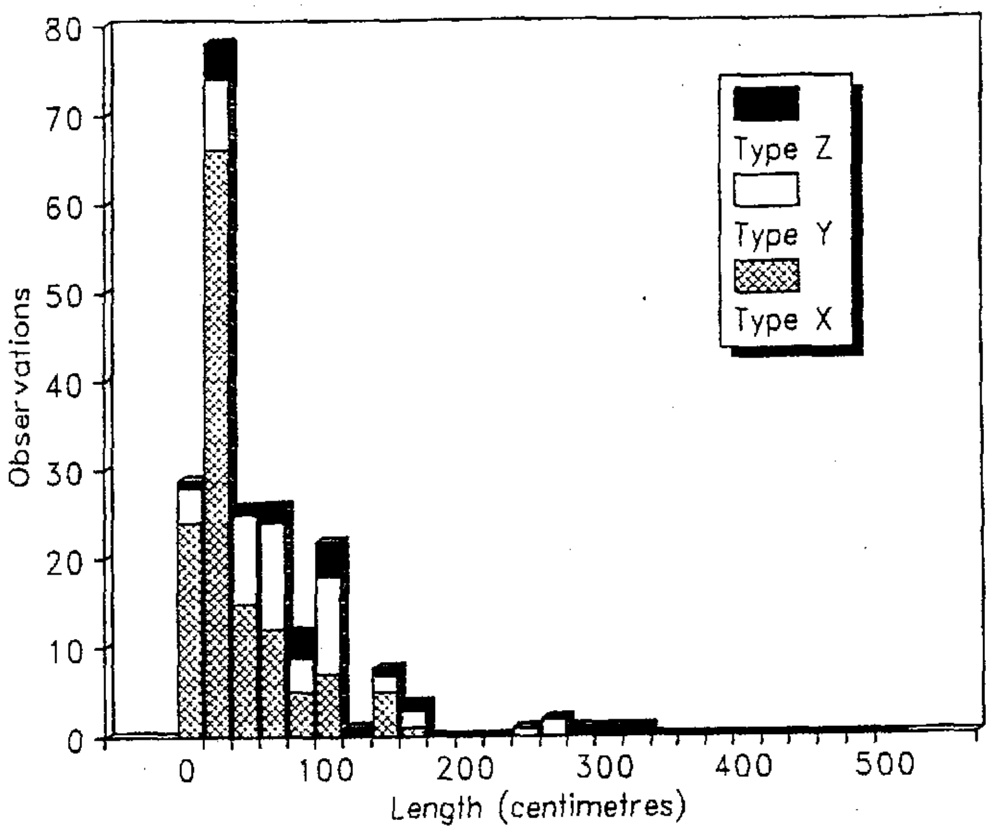


Figure 62. Vertical Fracture Length Distribution, Upper Snow School Till.

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