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ASPECTS OF SEDIMENTOLOGY AND FLUVIAL MORPHOLOGY OF A PART OF THE LITTLE MISSOURI RIVER, NORTH DAKOTA

by
Paul C. Jeffcoat-Sacco

Bachelor of Arts, University of Maine, 1973

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

August
1979

979
35

This thesis submitted by Paul C. Jeffcoat-Sacco in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

John R. Reid
(Chairman)

Lee C. Gerhard

Alan M. Cvancara

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

A. William Johnson
Dean of the Graduate School

Permission

Title ASPECTS OF SEDIMENTOLOGY AND FLUVIAL MORPHOLOGY OF A PART OF THE LITTLE MISSOURI RIVER, NORTH DAKOTA

Department Geology

Degree Master of Science

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Date 2 August 1979

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ACKNOWLEDGMENTS

I would like to thank my committee chairman, John Reid, for his guidance, suggestions and his patience. Lee Gerhard and Alan Cvancara, committee members, critically reviewed this paper, and did much to encourage brevity and clarity of style. The North Dakota Geological Survey provided financial support for the field portion of this study, and Lorraine Rose was a helpful, willing and always available typist.

To my wife, Illona, you have been kind, indulgent and patient, a source of encouragement, and an uncomplaining companion, for which I am deeply grateful.

ABSTRACT

The Little Missouri River drains 21,500 km^2 in Wyoming, Montana, and the Dakotas. The river is perpetually muddy, although the bulk of its deposits are fine to medium silty sand. The discharge ranges between 0 and 3000 m^3/s, with a mean value of approximately 17 m^3/s.

Between Medora, North Dakota and Lake Sakakawea 250 km downstream, the river changes from meandering to braided. Braiding may be a transitory response to the decrease in discharge following the spring flood, although more likely braiding is the result of post-glacial changes in drainage, when the river was diverted eastward from its original course. Diversion, and perhaps continued up-lift of the Little Missouri Badlands, increased the channel slope and induced braiding. Aggradation in the braided portion of the river was probably initiated by impounding Lake Sakakawea.

Sediment mineralogic composition depended on clast size, with coarser sediment dominated by lithic fragments and quartz, and finer sediment characterized by quartz and chert. The distribution of all species of clasts, with the exception of pitted quartz, was size sensitive, in that each size interval had its peculiar mineralogy. The percentage of pitted quartz remained nearly constant because pitted quartz is perhaps the most stable clast type.

Two varieties of quartz were recognized. Rounded, pitted quartz was presumed to have been through several transport and deposition cycles. Clear, glassy, angular quartz was thought to be derived from igneous or

volcanic rocks, and to have been exposed to little transport. The proportion of angular quartz to total quartz increased from 0.04 in the -1 phi size class, to 0.4 in the 4 phi size class.

The ratios of quartz/quartz plus feldspar generally were greater than 0.8, and compare well with quartz/quartz plus feldspar ratios reported for the Bullion Creek Formation. Similar ratios for other strata in the drainage basin are unknown.

The mineralogic composition of the sediments in the Little Missouri River varied in an irregular manner over the stream course. The variation seems related to inputs of different sediments by the ephemeral tributaries. Therefore I conclude that local source variations are more important than fluvial processes in determining the mineralogic composition of the Little Missouri River sediments.

INTRODUCTION

Rivers, throughout history, have served man in a variety of ways. They provide water for his personal use, his animals, his crops, and his industries. Food can be found in, or near by, rivers. While walking was the earliest form of transportation, surely floating down a river was one of the first alternatives. And, all too often, rivers have been garbage and sewage removal systems. Even after a river dries up and is covered by successive strata, its bed may host ground water supplies, petroleum or mineral deposits.

For all the use made of rivers, we apparently know little of how rivers work, partly because certain fluvial parameters such as sediment load, amount of turbulence and mechanical energy distribution cannot be measured reliably and partly because we do not understand the relationships between those parameters that can be measured (Bogardi 1974). Consequently, much of our knowledge of rivers is empirical, and, while valid locally, it may not be applicable generally.

Fluvial studies appear to divide into two groups. One set of studies concerns itself with descriptive geomorphology, the other attempts to mathematically describe fluvial processes. Examples of the first group are Schumm (1956, 1960, 1961, 1963a, 1963b) and Leopold (1962), whereas examples of the second group are Einstein (1950), Bogardi (1974), Sundborg (1956) and Graf (1971). Bogardi (1974), for example, presented an excellent review of the recent work done in attempting to derive a sediment transport equation for universal application. My

study properly fits into the first group, largely because any natural system contains far more variables than may be conveniently or accurately measured.

The impetus for this study was provided by the observations of L. C. Gerhard and T. A. Cross, University of North Dakota. Gerhard and Cross (Cross 1976), while on a reconnaissance trip along the Little Missouri River. noticed that the mineralogy of the recent sediments varied in an unusual manner. A specific mineral was present at one location, absent at the next location downstream, and present again still farther downstream. Such a distribution of minerals, if it could be documented, seemed to oppose the generally held concept of sediment mixing in a fluvial environment. Additionally, Gerhard and Cross recognized two distinct quartz populations in the sediments. One population was composed of cloudy to milky grains having generally frosted or pitted surfaces. The grains in this population were noticeably rounded, indicating one or more episodes of transport by water. The other population was composed of clear, glassy, angular grains that presumably were subjected to little fluvial transport. The presence of a distinctive mineral, such as angular quartz, in sediments is often useful in discovering the source, or sources, of the sediments.

Purpose

This study proposes: (1) to describe a segment of the Little Missouri River, with particular attention being given to the mineralogy and grain size distribution of the recent sediments; and (2) to use the data generated in the mineralogic and grain size analysis to infer the possible source areas of the sediments.

Area of Study

The study area consists of the portion of the Little Missouri River lying between the town of Medora and Lake Sakakawea, a large man-made reservoir in the west central North Dakota (Figure 1). The river, in the study area, flows north and east, with a channel length of approximately 250 km, and crosses both units of Theodore Roosevelt National Memorial Park. Access to this area is limited; only a few roads serve the widely scattered ranches. The rugged badlands terrain and the presence of the national park prohibit the use of off-road vehicles to traverse the study area; therefore, the only practical means of visiting the entire area is by canoe or horse.

Geologic Setting

The Little Missouri River drainage basin covers 21,500 km^2 in Wyoming, Montana and the Dakotas (USGS 1967). With the possible exception of Beaver Creek, the Little Missouri River is the only permanent stream in the study area. There are, as will become evident, countless ephemeral streams that are significant if the distribution patterns exhibited by the Little Missouri River sediments are to be fully comprehended. As it enters North Dakota, the Little Missouri River crosses the northwest-trending Cedar Creek Anticline and flows into the center of the Williston Basin. The river, therefore, flows stratigraphically up-section.

Table 1 shows the sequence of rock units exposed in the drainage basin. Bullion Creek and Sentinel Butte Formations are the units most commonly exposed in the Little Missouri Badlands.

Fig. 1. Map of the Little Missouri River drainage basin. Study area is between Medora and Lake Sakakawea.

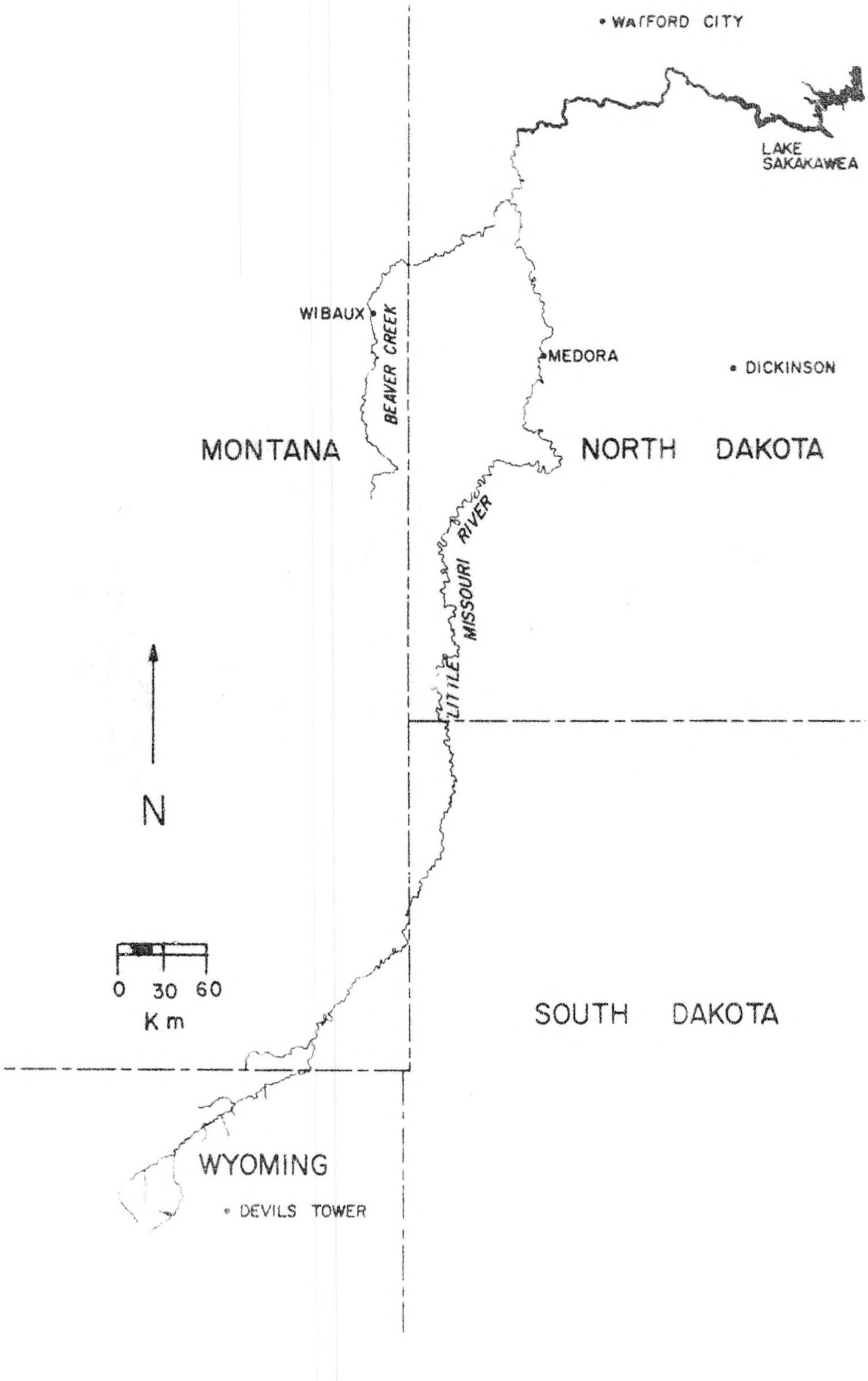

WATFORD CITY
LAKE SAKAKAWEA
WIBAUX
BEAVER CREEK
MEDORA
DICKINSON
MONTANA
NORTH DAKOTA
LITTLE MISSOURI RIVER
N
0 30 60
Km
SOUTH DAKOTA
WYOMING
DEVILS TOWER

TABLE 1

ROCK UNITS EXPOSED IN LITTLE MISSOURI DRAINAGE BASIN
(from numerous sources)

Age	Formation	Maximum Thickness (m)	Description
Quaternary alluvium		15	Unconsolidated slopewash and fluvial sediment, glacial sediment
Oligocene	"Killdeer"	25	Light gray fluvial sandstones, siltstones, and lacustrine limestone
Oligocene	Brule	20	Light yellow to light gray clays and sandstones, generally fluvial
Oligocene	Chadron	30	Light yellow to light gray calcareous clays and sandstones, arkosic pebbles locally, generally fluvial
Eocene	Golden Valley	65	Bright yellow clays and sandstones, fluvial and paludal
Paleocene	Sentinel Butte	300	Dull gray silt, clay and sandstones with lignite beds, fluvial and paludal
Paleocene	Bullion Creek	300	Light yellow silt, clay, and sandstones with lignite beds, fluvial and paludal
Paleocene	Slope	25	Brownish gray clay, silt, and sandstones with lignite beds, fluvial and paludal
Paleocene	Cannonball	55	Yellowish brown mudstone and sandstone, dark gray shales in lower part, marine
Paleocene	Ludlow	60	Gray to brown silt, clay, and sandstones with lignite beds, fluvial and paludal
	Hell Creek	180	Dark grey to brown silt, clay, and sandstones, fluvial and deltaic

TABLE 1--continued

Age	Formation	Maximum Thickness (m)	Description
Cretaceous	Fox Hills	100	Brown to gray marine sandstone and shales, transition from deep water to shore
	Pierre	20	Dark gray shale, gypsiferous, pelagic

A history of the drainage basin is outside the scope of this paper. Two events, however, are important for an understanding of the basin. The Little Missouri River originally flowed northward, discharging into ancestral Hudson's Bay, but was forced eastward by advancing ice during the glaciation of central North America (Leonard 1916). This diversion rejuvenated the stream, increasing its erosion rate. There is evidence also that the entire Badlands area still may be rising (Scattolini 1978). If indeed the area is rising, erosion may be increased. Regardless, increased flow after diversion resulted in a greatly increased amount of sediment being fed into a stream.

Local relief in the drainage basin presently often exceeds 300 meters (Hares 1928), especially in the Badlands several kilometers either side of the river. The bulk of the fluvial sediment in the thesis study segment may be presumed to be from rock units exposed in the Badlands, as these units are most subject to erosion. If this assumption is correct, nearly homogenous sediment is fed into the river.

Climate and Hydrology

The climate in the study area, and not incidentally, in the entire Little Missouri River drainage basin, is typically continental.

The seasonal temperatures vary over a wide range. Rapidly advancing weather fronts produce large day-to-day changes in temperature. The relative humidity is low, precipitation is generally light overall, with spotty coverage, and the wind is nearly continuous. Table 2 shows several parameters of the local climate measured in western North Dakota, and should be considered typical of the entire drainage basin.

TABLE 2

SOME CLIMATE PARAMETERS AT MEDORA, NORTH DAKOTA
(from Jensen 1972)

	Mean Annual	Mean April-July	Mean April-Sept	Annual Extremes
Temperature (C)	5.6	14.4	15.6	+38, -35
Precipitation (mm)	356	208	292	
Days 0 C or below: 190				

The Little Missouri River is a small stream. Its discharge ranges over several orders of magnitude. The highest discharge recorded was 3,120 m^3/s on March 25, 1947. There usually is no flow during winter months, and but little flow in late summer and fall.

The discharge of the Little Missouri River, measured at the USGS gaging station near Watford City, North Dakota, may be used directly as total runoff of the basin. These records, begun in 1934, show an average discharge of 16.8 m^3/s (USGS 1967). An average measurement, however, gives but little understanding of any parameter. Along with the calculated average, it is necessary to have some idea of how a parameter varies with time, and over what range it varies. From table 2 it can

be determined that 60% of the annual precipitation occurs between April and July. In addition, 80% of the total precipitation occurs between April and September (Jensen 1972). An examination of basin runoff should disclose a variation nearly congruent to the variation in precipitation, except where the runoff pattern is modified by spring thaw; the annual increase in runoff generally precedes the increase in precipitation (Figure 2). This incongruous sequence, where precipitation lags runoff, is equally explained by recognizing that the winter snow cover serves as a water storage mechanism. The spring thaw releases water that is not absorbed by the still frozen soil; most enters the river.

Method of Study

Field Procedure

The field work for this study was done in June and July of 1978. Forty-seven 500 g samples were collected from recent deposits of a segment of the Little Missouri River (Figure 3), placed in cloth bags, numbered, and returned to the laboratory for further study. The distance between sampling sites, nearly as practicable, was 4.5 km measured along the river. Initially, all sample sites were to be located near water's edge on a pointbar. It proved impossible to adhere to this scheme, however, as the stream channel pattern changed from meandering to braided over the course of the studied segment. Where necessary, therefore, braid bar sites were substituted for point bar sites. Channel geometry and stream character were noted at each sampling site.

The field traverse was terminated 15 km short of Lake Sakakawea, where the shallow river depth prohibited further travel by canoe.

Fig. 2. Discharge of the Little Missouri River, 1972. Measured at the USGS Gaging Station near Watford City, North Dakota. The year 1972 was wetter than usual, although the flow increases three orders of magnitude almost every year during spring thaw.

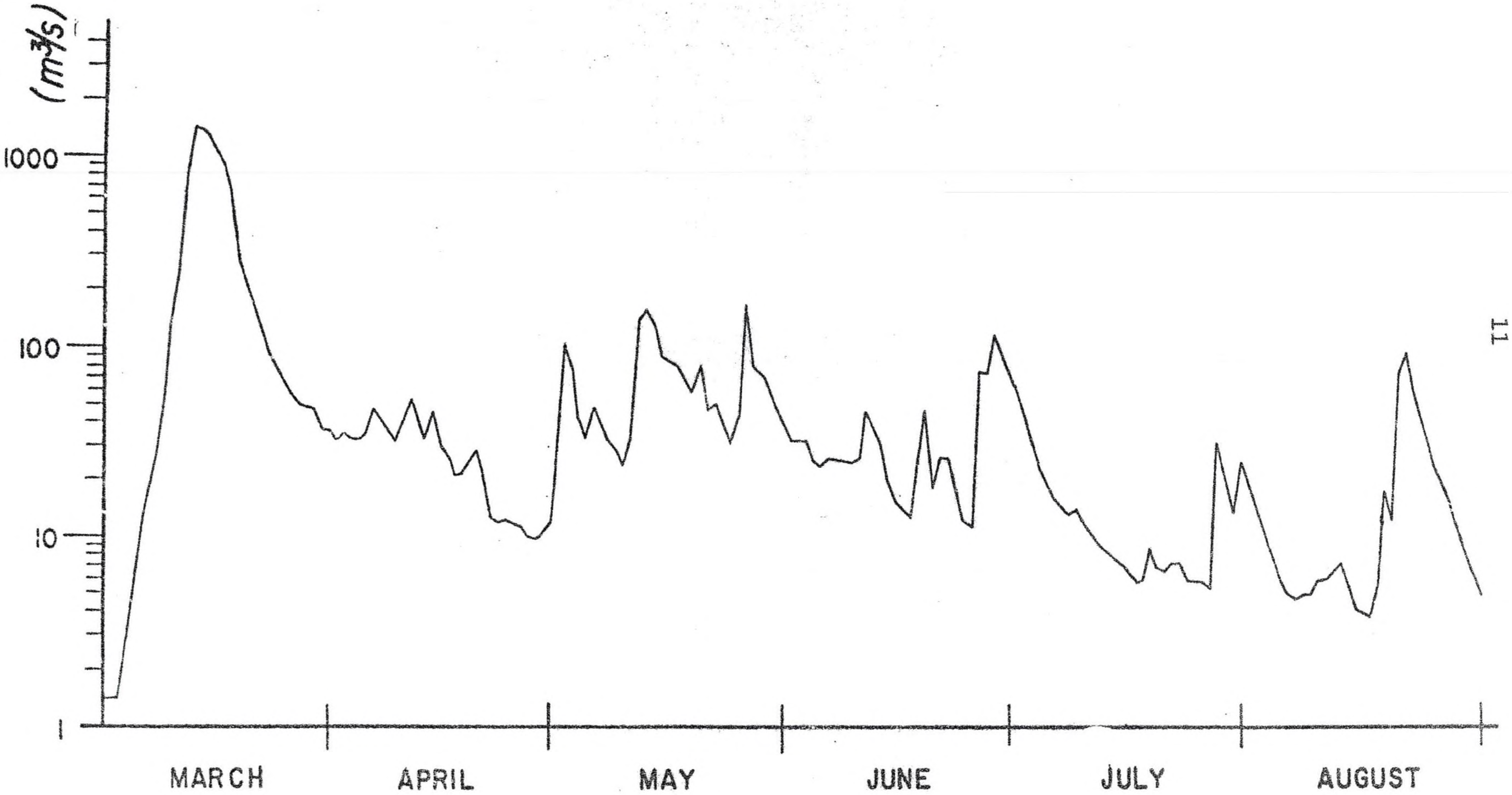
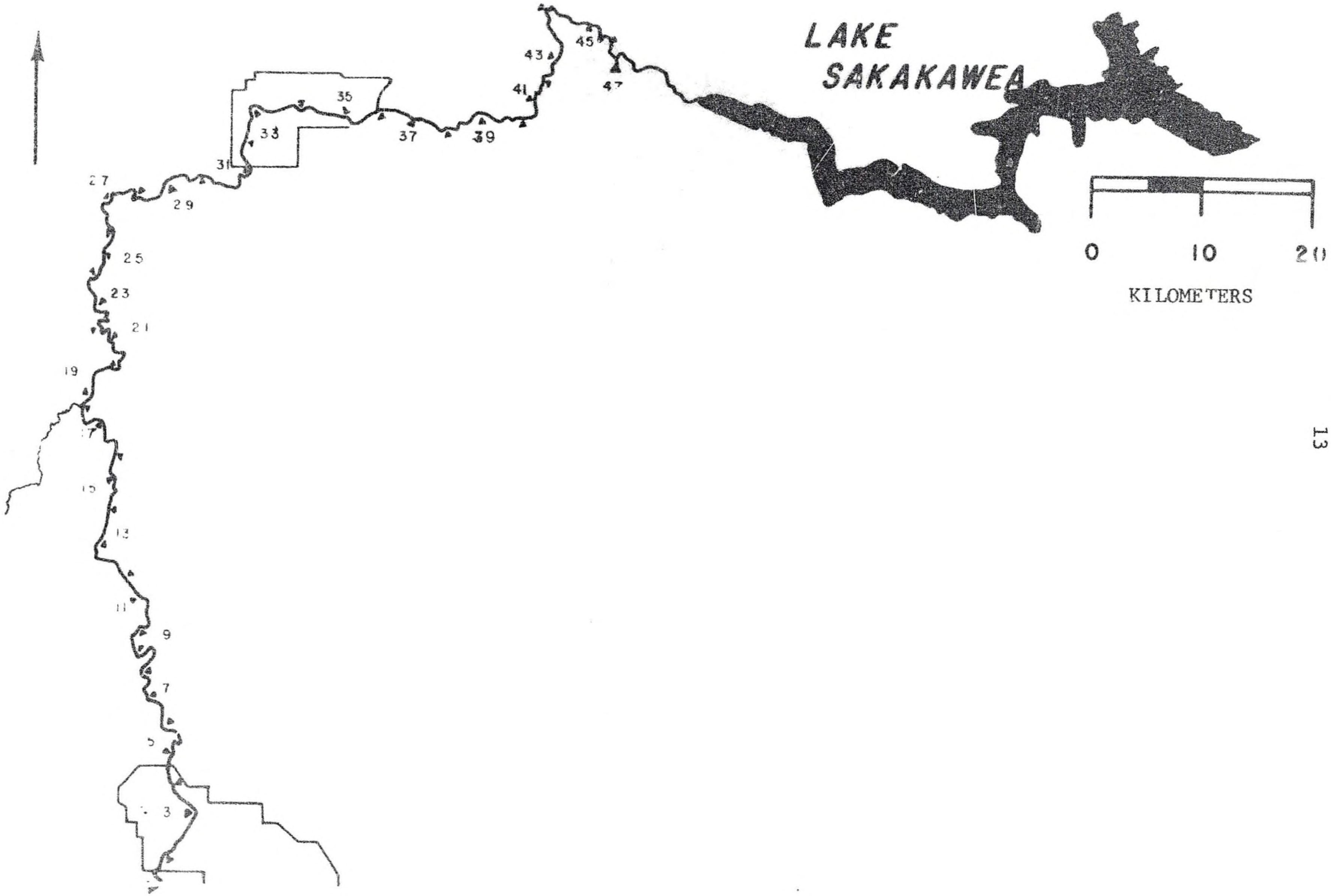

(m³/s)
1000
100
10
1
MARCH
APRIL
MAY
JUNE
JULY
AUGUST

Fig. 3. Map of the study area showing sampling sites. Every other site numbered, but all sites are shown. Both units of Theodore Roosevelt National Memorial Park are outlined. Medora is just south of the south unit.


LAKE
SAKAKAWEA
0
10
20
KILOMETERS
3
5
7
9
11
13
19
21
23
25
27
29
31
33
35
37
39
41
43
45

Laboratory Methods

A laboratory sample consisted of a 100 g statistical split of an air-dried field sample. Each laboratory sample was immersed in distilled water, placed in an ultrasonic bath for fifteen minutes, and then wet sieved into one-phi intervals, over the range -2 phi to 4 phi. Grains smaller than 4 phi were discarded. After sieving, each size fraction was oven dried at 40°C, and weighed to the nearest 0.1 gram. The weight of silt plus clay was determined by subtracting the total weight of the larger grains from 100 g.

The sand-size clasts were then mounted on glass slides, according to sample and phi size. Three hundred grains on each slide were identified and counted to determine the mineralogy of each sample. The area method of point counting was used, and the data yielded were number percent (Galehouse 1970). The maximum probable error of any one of the individual components, at the 95 percent confidence level, was less than six percent.

Theoretically, there should have been 47 (number of samples) x 7 (size of intervals per sample) = 329 slides prepared for point-counting. There were fewer because some size intervals of several samples had fewer than 300 grains, as determined by a comparison of the measured weight to a calculated average weight for 300 grains of each size class.

Previous Work

Mineralogy and Petrology of the Area

Petrologic studies of the formations exposed in the drainage basin are sparse, although some of the stratigraphic studies contain useful

sections dealing with petrology and mineralogy. One difficulty arises in interpreting the available information because I used grain mounts for mineralogic analysis, whereas most of the previous data are derived from thin sections. The two analytic techniques yield different types of data; grain surface features are not observable in thin sections, and feldspars and lithic fragments are difficult to subdivide by type in grain mounts.

The petrology of the Fort Union sandstones was first studied by Tisdale (1941). He found the most abundant minerals to be quartz and feldspar. The generally subangular shape and undulatory extinction exhibited by the quartz grains caused Tisdale to suppose that some of the grains were derived from metamorphic rocks. He also included a large list of heavy minerals found in the Fort Union interval. Similar results were reported by Crawford (1967), Cherven (1973), and Johnson (1973).

Steiner (1978) determined that the Sentinel Butte and Bullion Creek Formations may be differentiated on the basis of quartz to feldspar ratios. Higher ratios are found in the Bullion Creek Formation.

Hares (1928) reported finding angular quartz and fresh feldspars in the Fox Hills, Hell Creek and White River Formations. Sigsby (1966) noted the freshness of feldspars in sandstones of the Fort Union Formation, although he did not differentiate the angular quartz grains from the total quartz population. Frye (1967), in a rather complete description of the Hell Creek Formation, and Johnson (1973), working in the Sentinel Butte Formation, each found abundant quantities of angular quartz. Angular quartz and fresh feldspars were generally interpreted as indicative of little or no transport, especially fluvial transport.

Fluvial Geology

The United States Army Corps of Engineers (Corps) studied some aspects of the Little Missouri River before and after the impoundment of Lake Sakakawea in 1953. Sediment input into the lake was measured, and the stream channel was surveyed at intervals. The channel surveys showed noticeable aggradation near the lake.

Schumm (1956, 1960, 1961, 1963a, 1963b), in a remarkable series of papers, detailed morphological aspects of several streams in the plains of North America. All the rivers included were similar to the Little Missouri River.

Several other researchers have summarized the historical development of sediment transport theory and fluvial mechanics. I found Henderson (1966), Graf (1971), Bogardi (1974), and Garde and Ranga Raju (1977) to be thorough and surprisingly readable volumes. In addition, short papers on various aspects of modern transport theory were found in the proceedings of seminars sponsored by the Corps (1970) and the Water Resources Council (1976). Shen (1972) edited a collection of papers presented at a symposium honoring H. A. Einstein. Two papers by Einstein (1942, 1950) were included in the collection, the earlier of which was the first application of probability theory to the field of sediment transport.

Schmitz (1955) proposed a sequence of stream captures which resulted in the eastward diversion of the originally north-flowing Little Missouri River. The stream captures presumable were caused by increased erosion due to the precipitation increase immediately prior to the advance of Kansas-Illinoian ice into western North

Dakota. He mapped five levels of terrace development in the river valley. Particularly interesting is Terrace 2, which he thought developed by down-cutting of the channel at the time of retreat of the last continental ice sheet. Everitt (1968) analyzed growth rings of cottonwoods in a part of Schmitz's study area. From these data, he postulated that Terrace 2 (Schmitz 1955) could be only about 300 years old, and was composed of slope wash and fluvial overbank sediments; therefore, Terrace 2 was not a terrace but a flood plain.

MORPHOLOGY OF THE LITTLE MISSOURI RIVER

Over its course, the Little Missouri River changes from a meandering stream to a braided stream. It is convenient, therefore, to divide the river into two sections when describing its morphology. The dividing point between the two sections lies approximately 165 river km downstream from Medora. Although no abrupt change in the character of sediments exists, the mechanics of sediment input are quite different in the two sections. The change in mechanics does produce changes in sediment character and depositional processes, although these changes are subtle. The most striking change is the construction of what appear to be small shelves of clayey silt along each bank at near water level. I have supposed these deposits to result from water losses to the stream banks, which strain out the silt much as filter paper strains out chemical precipitates.

The location of the dividing line between the meandering and braided portions of the river is a transitional zone. The highly variable discharge rate of the stream (Figure 2) probably causes the transition point to shift back and forth over several kilometers. Lane (1955) provided a relationship,

$$Q_s \times d \propto Q_w \times S$$

where Q_s = sediment discharge, d = particle diameter, Q_w = water discharge, and S = slope. This relationship is a statement of equilibrium conditions, and if water discharge increases, one or more of the other

variables must respond in such a manner as to cause a return to equilibrium.

The Meandering Channel

The meander amplitude (Leopold, Wolman, and Miller (1960) occasionally exceeds one kilometer, but is generally less than one-half kilometer. The tortuosity of the channel (Schumm 1963a) is variable. The channel is more tortuous in areas where the banks are more lithified. An example of great channel tortuosity may be found at Wind Canyon in the South Unit of Theodore Roosevelt National Memorial Park. Channel sinuosity, which is defined as channel length divided by down-valley distance (Leopold, Wolman, and Miller 1960, Schumm 1963a), has a value of 1.8, and width to depth ratios are always in excess of 30:1. The channel cross section is best represented by a steep-sided trapezoid, where the included angle between channel bed and wall lies between 90° and 135°. The mean flow velocity is approximately 0.7 m/s, and the channel width is usually between 30 and 50 meters. There channel parameters were measured when the discharge was only about 40 m^3/second; they probably change drastically during periods of high discharge.

Streams in flood tend to straighten their channel by flowing over previously established point bars (Freidkin 1945, Leopold, Wolman, and Miller 1960), but the same authors do not agree whenever channel bottoms are compared. Freidkin (1945) stated that increased discharge need not cause channel scour, but personnel of the USGS gaging station at Medora report that spring floods are often accompanied by scour of more than two meters (Peay 1978). Evidence of channel straightening during spring flood exists in the flood damaged vegetation and bar deposits that are

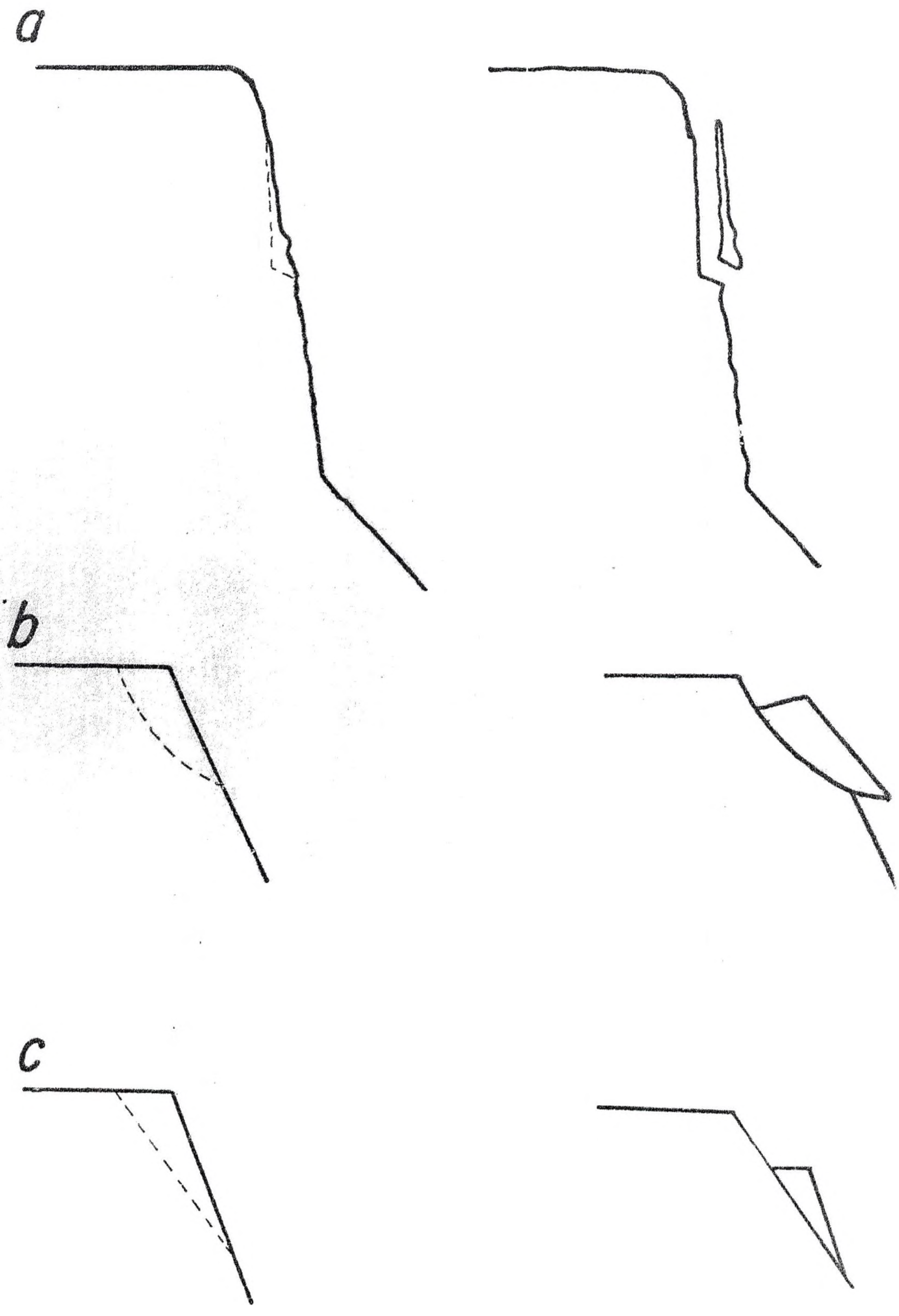
several tens of meters away from water's edge on point bars that were overrun by the stream.

The major sediment input mechanisms on this portion of the stream are slope wash and tributary flow. Although Beaver Creek is the only perennial tributary stream in this area, there are many ephemeral streams that dissect the poorly consolidated strata in the Badlands. Their number may be estimated. Schumm (1956) compared several characteristics of badland streams in Perth Amboy, New Jersey, to mature streams, and established that the drainage net at Perth Amboy is similar to the drainage patterns developed in semi-arid badlands in the western United States. The drainage density, the ratio of stream length to basin area, of mature streams did not exceed 20, while the drainage density at Perth Amboy was measured at 602. I have not measured the ephemeral streams in the Badlands, but if the drainage density of this 21,500 km^2 basin is even on the order of only 300, there must be more than six million kilometers of ephemeral stream channels that deliver sediment to the river during spring melt and periods of heavy rain.

One sediment input mechanism that contributes an unknown amount of debris to the stream is rather unusual. The cutbanks in some bends are near vertical, and rise more than 30 m above the water (Figure 4). These faces aperiodically shed several cubic meters of material into the stream. Episodes of shedding resemble rockbursts, although there is no appreciable amount of overburden (Figure 5). These debris falls sometimes may be initiated by sudden noises, such as slapping a canoe paddle on the water, and are perhaps controlled by vertical jointing on exposed surfaces.

Fig. 4. High walled cut-bank of meandering channel, about 40 km downstream of Medora, North Dakota. Rockburst-like shedding events typically occur in areas such as this. (Near sample site 21)

Fig. 5. Comparative figures showing development of slope failures typical in cliff face shedding event. a. rockburst-like failure; b. slump; c. slide.


a
b
c

The Braided Channel

A braided stream exhibits a greater slope, higher flow velocity, higher sediment concentration, greater width, and less depth than a meandering stream (Pettijohn, Potter, and Siever 1973). The channel often splits and rejoins (anastomoses) around shifting mid-channel bars. Braided channels are usually developed in areas where banks are easily eroded, and the sediment concentration is consequently increased (Leopold, Wolman, and Miller 1960, Henderson 1966, Reineck and Singh 1975, and Garde and Ranga Raju 1977).

Schumm (1971) offered several examples of streams which have changed from braided to meandering habit in response to altered con- conditions. He does not mention an instance of the opposite condi- tion, although he states that there is no physical reasor why the equations that describe such a change should not be valid. The 90 km of Little Missouri River channel immediately above Lake Sakakawea exhibit such a change from meandering to braided habit, accompanied by aggradation of the channel.

The channel in this part of the study area meanders, and is between 50 and 85 meters wide. In places, the depth does not exceed 0.1 m, although the usual depth is somewhat greater (approximately 0.7 m). The flow braids around numerous mid-channel bars, some of which are now islands that support grasses and small (less than 5 m) cotton- woods (Figure 6). Point bars are being eroded and are frequently capped with coarse gravel (Figure 7). This gravel cap is approximately 0.5 m thick, and probably represents a flood deposit.

The mean flow velocity in this section was about 1 m/s and much higher where the depth was reduced. The width to depth ratio was not

Fig. 6. Downstream segment of Little Missouri River with braid-bar in center of channel. (Near sample site 34.)

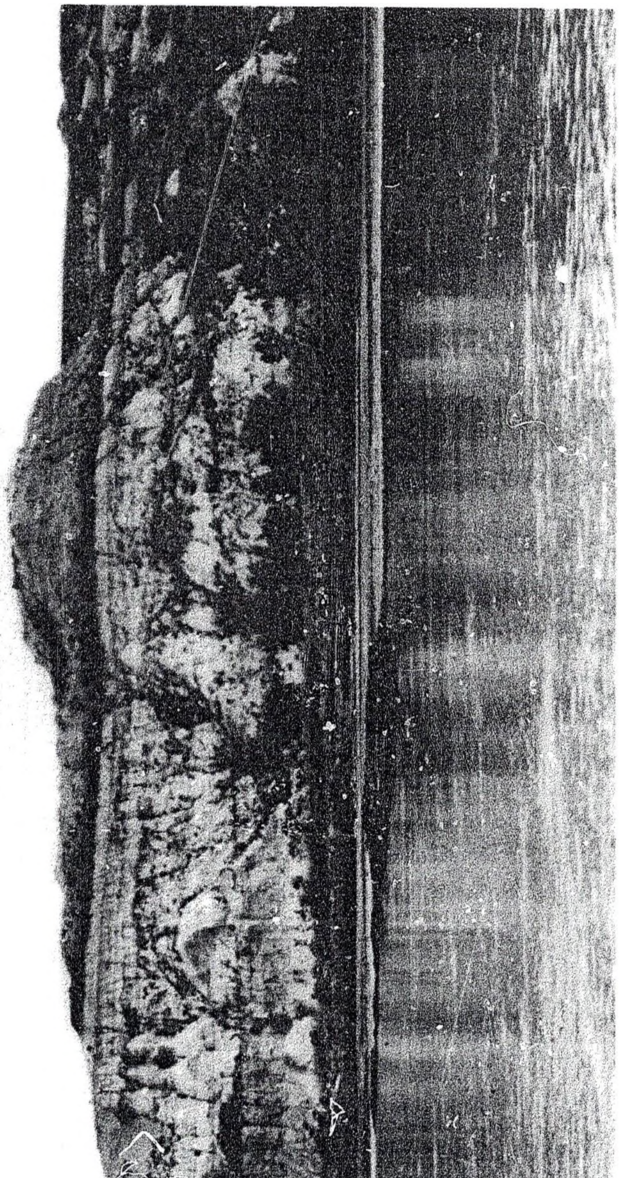


Fig. 7. An eroded point-bar capped with coarse gravel. (Near sample site 28)

calculated because I was unable to identify a typical channel width. The main channel is commonly bounded by steep banks of cross-bedded or plane-bedded fine to medium sand, which sometimes contain buried plant material (Figure 8), or alternating layers of massive sand and silt (Figure 9).

The rate of bank erosion may be estimated from Figure 9, which shows a small tree extending horizontally over the stream. The tree has not been in a horizontal position long enough to show heliotropism. I have observed slump blocks in the river which rose two meters above the water, and had a volume of nearly 50 m^3. These slump blocks may be completely eroded in a few weeks (Fenton 1978).

I do not know when the lower portion of the Little Missouri River developed its braided habit, but as braiding was not mentioned in any previous work, I concluded that it is a recent phenomenon. Conditions which may contribute to the development of a braided channel in this section are:

1. Construction of Lake Sakakawea. The construction of Lake Sakakawea in 1955 raised the base level. A raised base level induces aggradation in order to adjust the stream profile in the equilibrium direction (Lane 1955). In addition, back-water effects of reservoir storage cause a decrease in stream velocity, and consequently, a decrease in sediment transport capacity (Fan 1976). The increased sediment concentration (load) which induces braiding often is accompanied by channel aggradation as here, but aggradation and braiding need not occur together (Leopold and Wolman 1957). In short, braiding is a response to increased sediment load, and aggradation is a response to velocity decrease. Despite back-water effects from Lake Sakakawea,

Fig. 8. Cut Bank of the Little Missouri River. Composed of plane bedded sand and massive silt, probably channel and overbank deposits. (Near sample site 30).

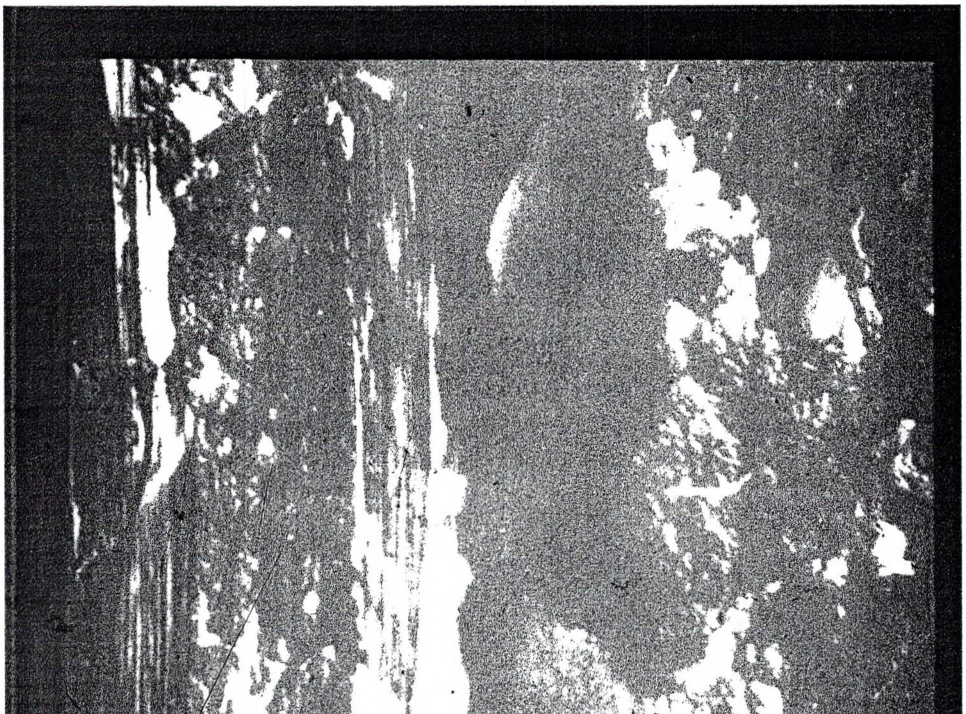
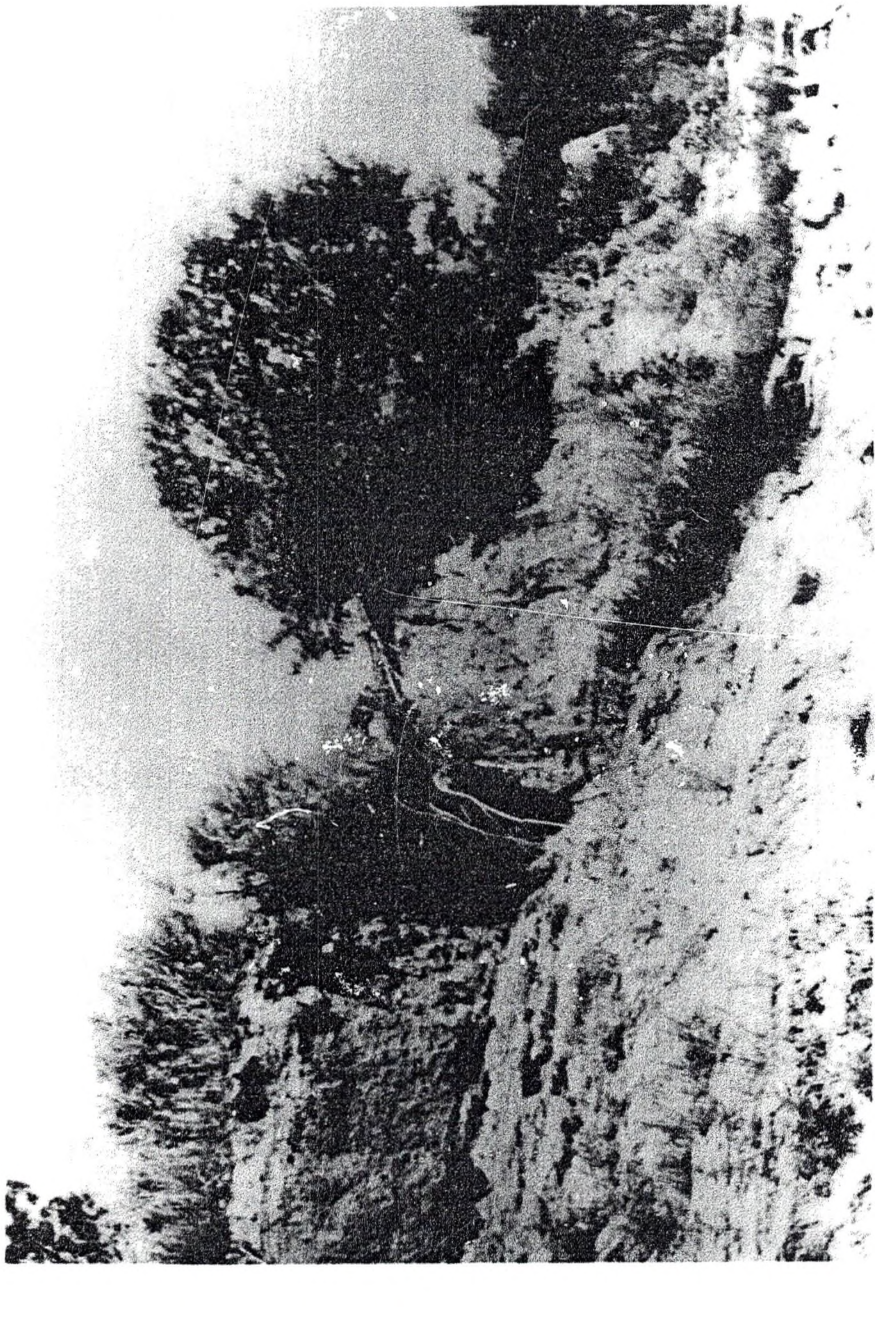


Fig. 9. Small tree extending horizontally from bank, demonstrating rapid erosion rate. Note that bank (2 m high) is composed of silt and sand beds. (Near sample site 40).



my measurements indicate that flow velocity in the braided channel is higher than in the meandering channel. The velocity increases on the lower part of the Little Missouri River, but the increase is limited by back-water effects from Lake Sakakawea. Velocity is insufficient to prevent channel aggradation.

2. Change in bank material. In this section of the river, the banks are of recent fluvial overbank deposits and large alluvial fans (Everitt 1968). In contrast, the banks of the meandering section upstream are composed of more resistant strata of the Bullion Creek or Sentinel Butte Formations. Increased bank erosion increases the sediment concentration by adding more sediment to a constant volume of water.

3. Change in bank permeability. The young overbank and alluvial deposits may allow the stream to lose water to its banks, which would increase the sediment concentration by removing water from a fixed volume of water-sediment mixture. Silt deposits along the channel walls seem to substantiate a water loss process. These silt deposits are usually less than 20 cm thick, and extend a few centimeters above the water surface. Because the river level varies, the upper portion of the deposits may be exposed. The deposits are perhaps formed because the bank captures sediment from the infiltrating water. It would be interesting to know whether these deposits, after attaining a thickness of approximately 20 cm, act as a natural grout, and prohibit further water loss to the banks.

While it may be possible that some combination of these factors is responsible for the observed braiding, it may also be that braiding is a transitory phenomenon, a response to the rapid decrease in discharge that immediately follows the spring flood. The lower part of

the stream may return to a meandering habit when the discharge falls below some threshold value.

PETROLOGY OF THE SEDIMENTS

Pettijohn, Potter, and Siever (1973) have reviewed the several methods used to classify sediments. Evident from this review is that no one method has been universally acknowledged as superior, but classification is usually based on grain size, texture, and mineralogic composition. The composition of sediments is usually determined by point counting grain mounts or thin sections. Any chosen method of point counting yields data that usually cannot be compared statistically to the results of another method of point counting (Galehouse 1970).

Descriptions of sediment texture may include information in grain shape, roundness, surface features, grain size, and fabric. Several parameters have been suggested to describe shape and roundness, none of which is to be preferred (Pettijohn, Potter, and Siever 1973). Any description of surface features involves subjective judgments that usually are not standardized or quantified. Granulometric analyses are routinely performed because they are quick, require little equipment, and yield hard data that statistically may be manipulated, albeit with highly variable results.

The clasts were separated into the following categories:

Angular quartz	Chert
Pitted quartz	Lithic fragments
Feldspar	Other
Mica	

Quartz grains were differentiated on the basis of surface features: pitted or frosted grains showing round edges were classified as Pitted Quartz; glassy, clear grains with no rounding (and often conchoidal fracture) were termed Angular Quartz. Pitted quartz grains were assumed to have been derived from sedimentary rock, and to have been exposed to several transport cycles. Angular quartz grains probably were derived from volcanic or acidic igneous rocks, and have not been extensively transported. The origin or transport history assigned to quartz grains by analyzing surface textures may be incorrect; surface textures are altered by chemical as well as mechanical processes (Jacka 1970).

Grains identified as lithic fragments probably included plutonic, volcanic, metamorphic and sedimentary clasts, although no attempt was made to differentiate among them. To have done so would have required thin section preparation.

Clasts that were identified as "Other" included:

Apatite	Kyanite	Tourmaline
Chlorite	Rutile	Zircon
Epidote	Sillimanite	Mollusc fragments
Garnet	Sphene	Petrified wood
Gypsum	Staurolite	Pumice

In no case did these clasts comprise one percent of any sample, and many samples contained none of these.

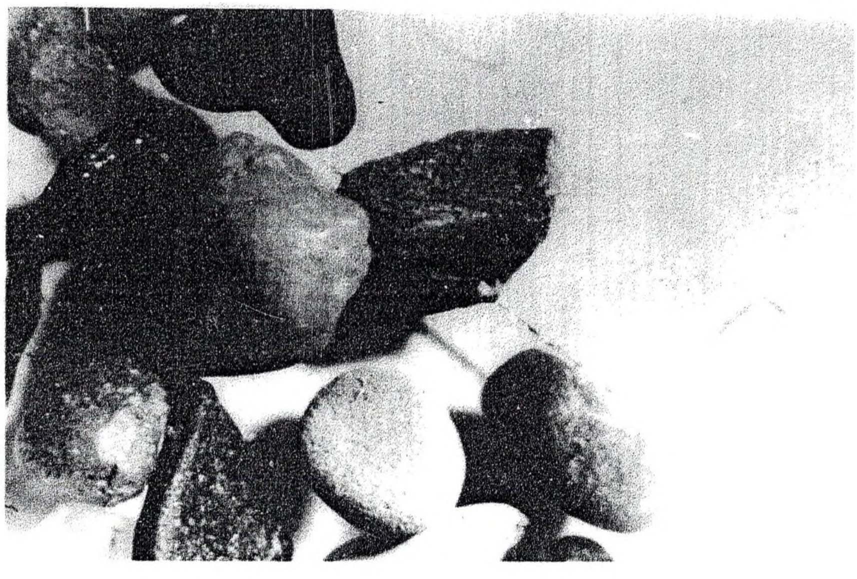
Some of the minerals are shown in Figures 10 through 13. Photomicrography was generally unsatisfactory, however, as the grain relief often exceeded the depth of field provided by microscope optics.

Fig. 10. Photomicrograph showing pitted quartz, feldspar (with cleavage), lithic fragments (dark grains) and mollusc fragment (blade-like grain in lower left). (30X)

Fig. 11. Photomicrograph with feldspar welded to quartz grain (in center). Note inclusions in quartz grains. (30X)

Fig. 12. Photomicrograph with angular quartz grain in center. (45X)

Fig. 13. Photomicrograph with gypsum (fibrous grain) near center. (35X)



Granulometry and Mineralogy

The river is depositing medium to fine silty sand. The sediment grain size decreases in a downstream direction (Figure 14). The mean of the fluvial sediment is considerably coarser than either Bullion Creek or Sentinel Butte sediments (Royse 1970). There are two ways to explain the coarseness of the fluvial sediments:

1. Hydraulic sorting. For a given amount of energy, more fine sediment will be transported than coarse sediment, or conversely, fine particles will be transported farther than coarse particles (Mackin 1948). The result is that coarser particles are left behind as a lag.

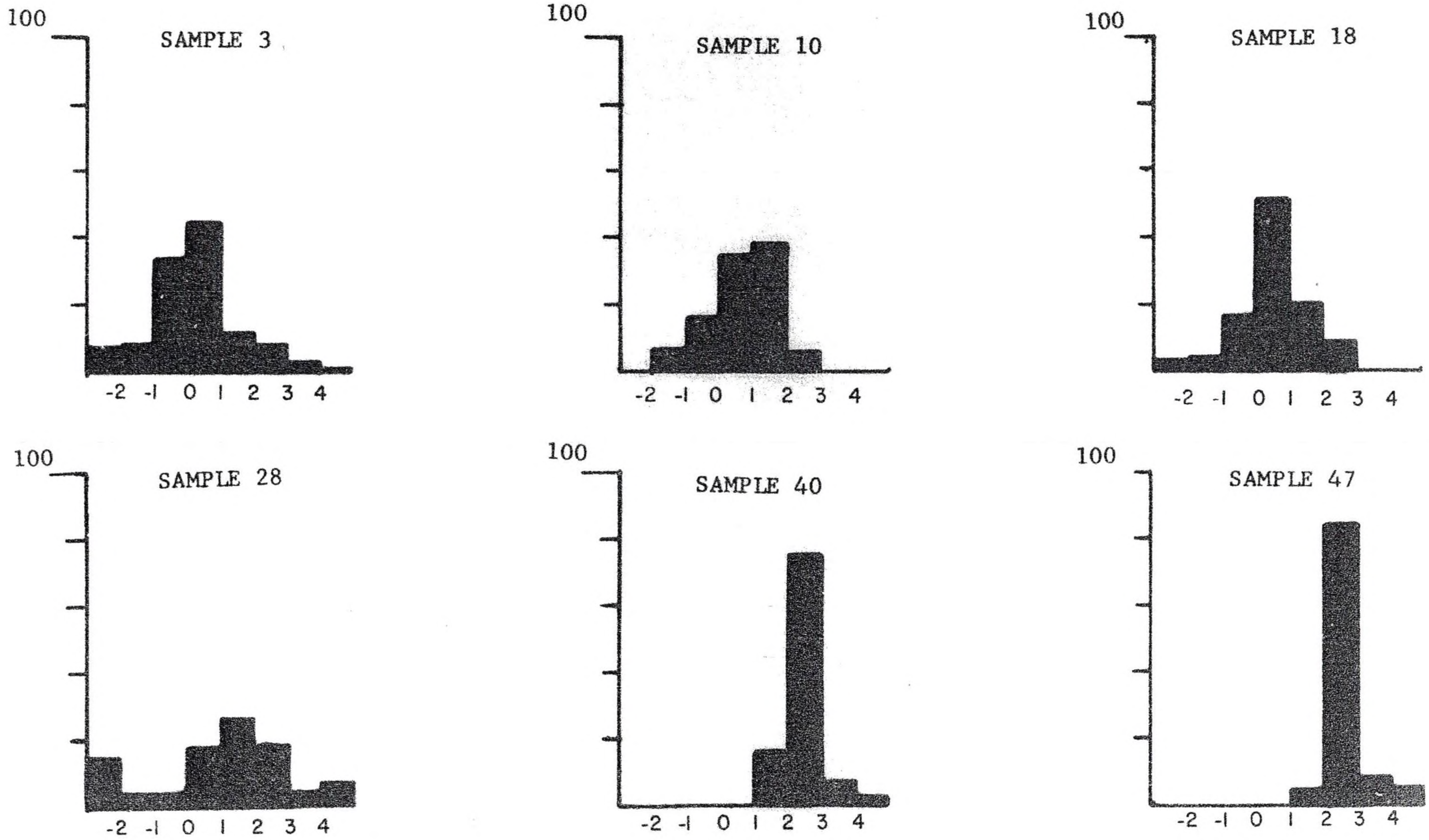
2. Differential erosion. Both Bullion Creek and Sentinel Butte Formations are composed of poorly lithified silts, sands, and clays. The sand bodies probably are more easily eroded than the silts or clays. If this is true, then the sediment fed into the stream has a coarser mean grain size than either formation.

Before summarizing the results of grain size measurements and mineralogic analyses, it must be stated that the samples do not represent bed load, but bed material load, defined (Einstein 1950) as sediment load that consists of particles present in the bed. The samples were drawn from stream deposits, and these, as was noted by Mackin (1948), may be quite different from the actual transported load. Data resulting from the laboratory analyses are included in appendices A and B.

The -2 phi Interval

The mineralogic composition of the -2 phi interval was not determined because I calculated that no sample contained the necessary 300 grains to be counted (see page 14). Samples 8, 13, 24, 26, and 28

Fig. 14. Histograms of grain size distribution, showing the change in size observed over the stream course.


100
SAMPLE 3
-2 -1 0 1 2 3 4
100
SAMPLE 10
-2 -1 0 1 2 3 4
100
SAMPLE 18
-2 -1 0 1 2 3 4
100
SAMPLE 28
-2 -1 0 1 2 3 4
100
SAMPLE 40
-2 -1 0 1 2 3 4
100
SAMPLE 47
-2 -1 0 1 2 3 4

(appendix A) each contained several large pebbles that accounted for most of the weight of the -2 phi interval in these samples. Sample 29, and all but two samples downstream of 29, had no grains in this size interval.

The -1 phi Interval

Fourteen samples contained at least 300 grains in the -1 phi size interval. Downstream of sample site 28, the -1 phi interval vanished (appendix A). Lithic fragments dominated this size interval (Figure 15). Angular quartz was but a small part of this size interval. No mica and few accessory minerals (Other) were observed.

No systematic downstream variation in the composition in this size interval could be determined.

The 0 phi Interval

Twenty-four samples contained grains in the 0 phi size interval. This interval was non-existent downstream from sample site 36. Lithic fragments and pitted quartz, respectively, were the most common clasts (Figure 15). No mica was observed, and few accessory minerals. Again, the composition remained essentially unchanged over the river course.

The 1 phi Interval

Twenty-nine samples, none below site 36, contained grains in this size interval. The most striking characteristic of this interval was the sudden large increase in the percentage of angular quartz, accompanied by a decrease in the percentage of lithic fragments (Figure 15).

The 2 phi Interval

This interval is present in forty-one of the samples, making this grain size, along with the 3 phi interval, the dominant size in the

Fig. 15. Mineralogic composition of the several size fractions of the sediments. Note that the composition varies with grain size.

A = -1 phi

B = 0 phi

C = 1 phi

D = 2 phi

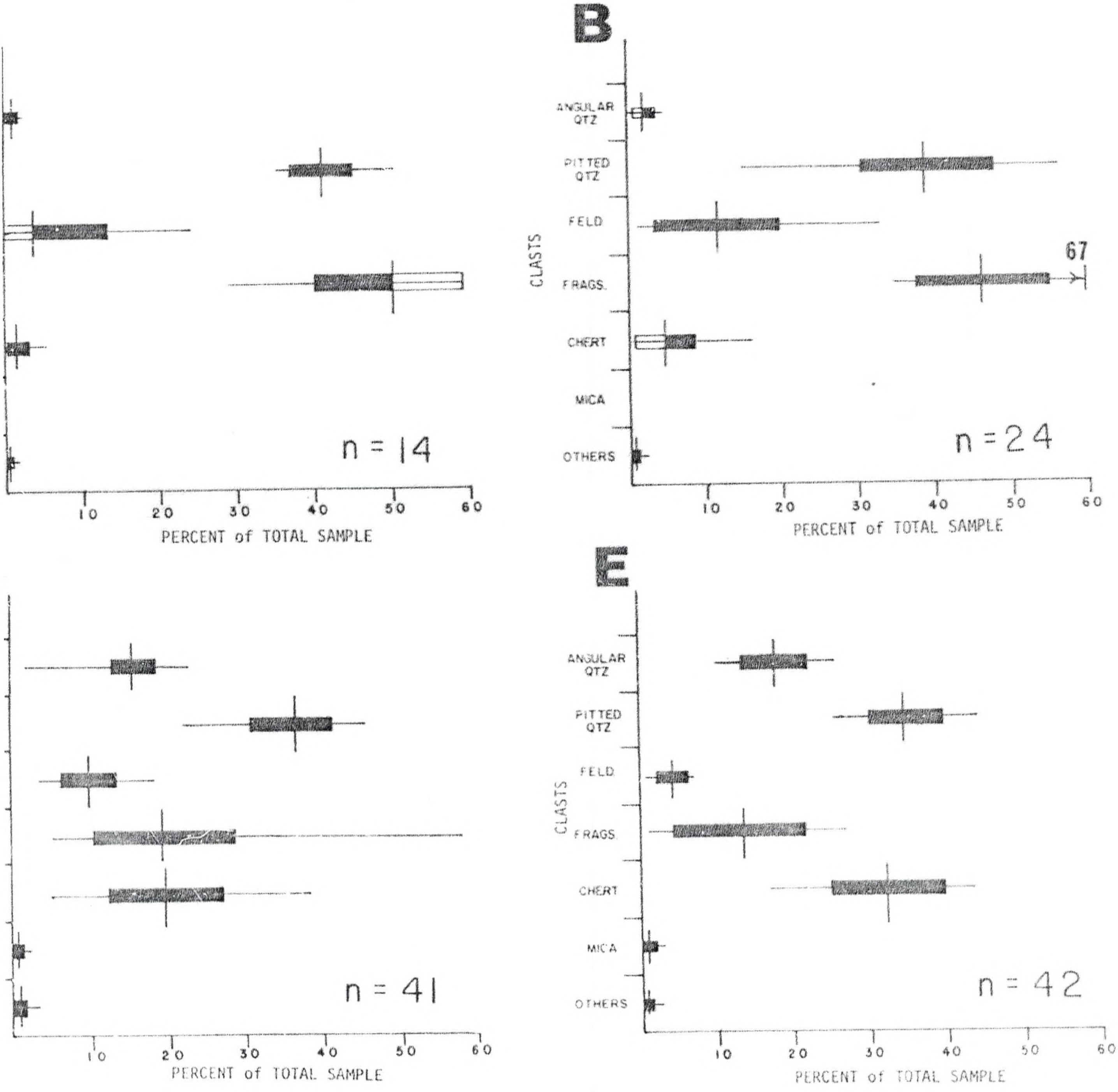
E = 3 phi

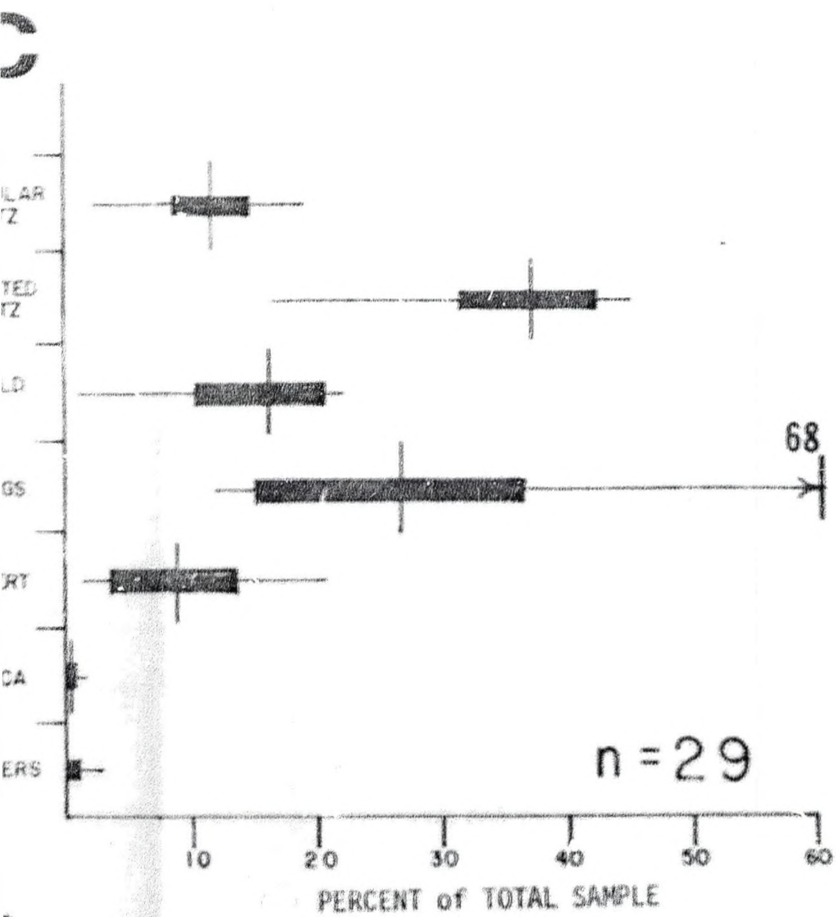
F = 4 phi

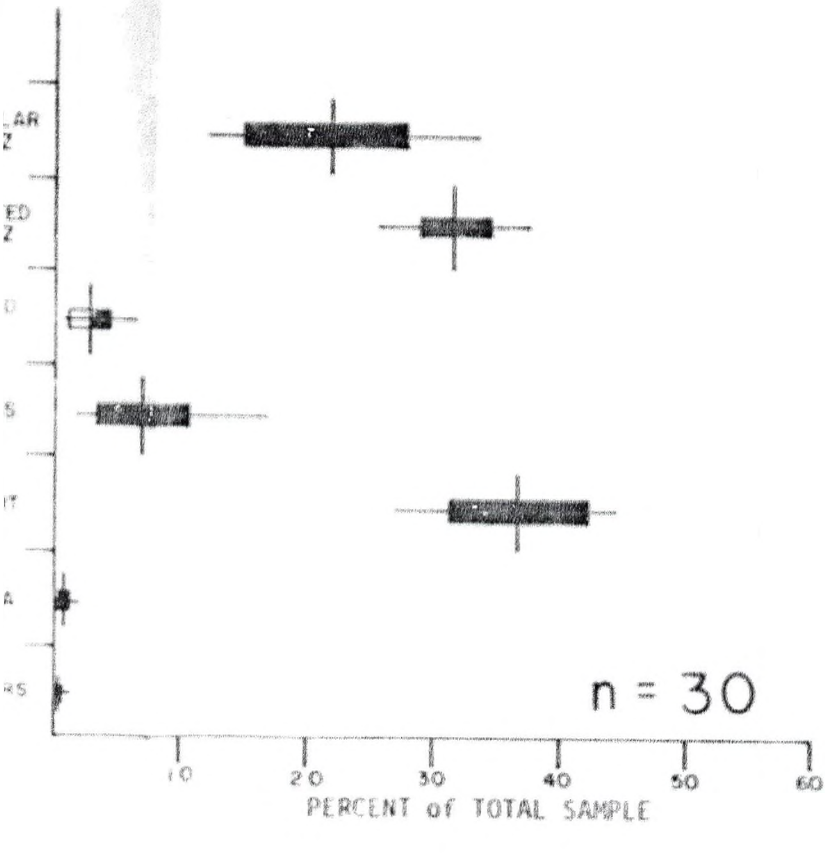
| = Mean

—— = Range

■ = Standard Deviation


n = 14
10 20 30 40 50 60
PERCENT of TOTAL SAMPLE
B
ANGULAR QTZ
PITTED QTZ
FELD
FRAGS.
CHERT
MICA
OTHERS
CLASTS
67
n = 24
10 20 30 40 50 60
PERCENT of TOTAL SAMPLE
n = 41
10 20 30 40 50 60
PERCENT of TOTAL SAMPLE
E
ANGULAR QTZ
PITTED QTZ
FELD
FRAGS.
CHERT
MICA
OTHERS
CLASTS
n = 42
10 20 30 40 50 60
PERCENT of TOTAL SAMPLE


68
n = 29
10
20
30
40
50
60
PERCENT of TOTAL SAMPLE


n = 30
10
20
30
40
50
60
PERCENT of TOTAL SAMPLE

sediments. No pattern of variation exists within this size interval, but chert increased dramatically over the size range from -1 to 2 phi (Figure 15). This increase appears to have been accomplished at the expense of lithic fragments. Increases in angular quartz, such as occur in samples 20 and 28 (appendix B) often are accompanied by a decrease in lithic fragments; but increases in lithic fragments are not always associated with decreases in angular quartz.

The 3 phi Interval

Forty-two samples contained grains in this size interval (Figure 15). Samples 23 and 30 (appendix B) perhaps illustrate instances where angular quartz and feldspar were confused, but when compared with samples 6 and 10, there appears to have been no such confusion of the two minerals, and the counts must be regarded as correct. I admit that four samples do not constitute a statistically valid test, but I selected these samples for illustration only. If the two minerals were confused, then the frequency of one probably would increase at the expense of the other (samples 23 and 30). An increased frequency for both minerals (samples 6 and 10) seems to argue against any but random misidentification.

The 4 phi Interval

Thirty samples were found to have grains in this interval (Figure 15). No significant change in the composition of this size interval was noted over the stream. Chert and angular quartz comprise more than fifty percent of the grains, and the frequency of lithic fragments is greatly diminished.

Mineral Distribution

I calculated the ratio of angular quartz/total quartz in an effort to determine where angular quartz first appeared in significant quantities. At no place did the ratios reveal a sudden increase in angular quartz, but when the ratios are plotted against grain size (Figure 16), it becomes evident that angular quartz is distributed in a size-related manner.

Ratios of quartz/quartz + feldspar (quartz/feldspar ratios of Steiner 1978) were calculated for comparison with similar ratios available for the Bullion Creek and Sentinel Butte Formations (Figure 17). Steiner (1978), for the Bullion Creek Formation, reported quartz/feldspar ratios generally greater than .89. The similarity of the ratios, however, is scant evidence to conclude that the Little Missouri River sediments are derived primarily from the Bullion Creek Formation.

Pettijohn, Potter, and Siever (1973) state that of the grains present in sediments, only lithic fragments usually show a size-related distribution. But for the sediments of the Little Missouri River, I found that all species of detrital grains were distributed in a size-related manner (Figure 15). Indeed, it appears that origin has more effect on sediment size and composition than fluvial processes do (Figure 18).

Because the sediment composition changes with grain size and the sediments were sorted by size, any change in mineralogy over the river course should be attributed to the size change of the sediments. I know of no satisfactory description of this sorting process, nor am I aware than it has been modeled mathematically. I am convinced that the sorting process will not be described adequately until the transport mechanism is better understood.

Fig. 16. Summary of angular quartz/total quartz ratios of the Little Missouri River sediments, showing variation between grain size intervals.

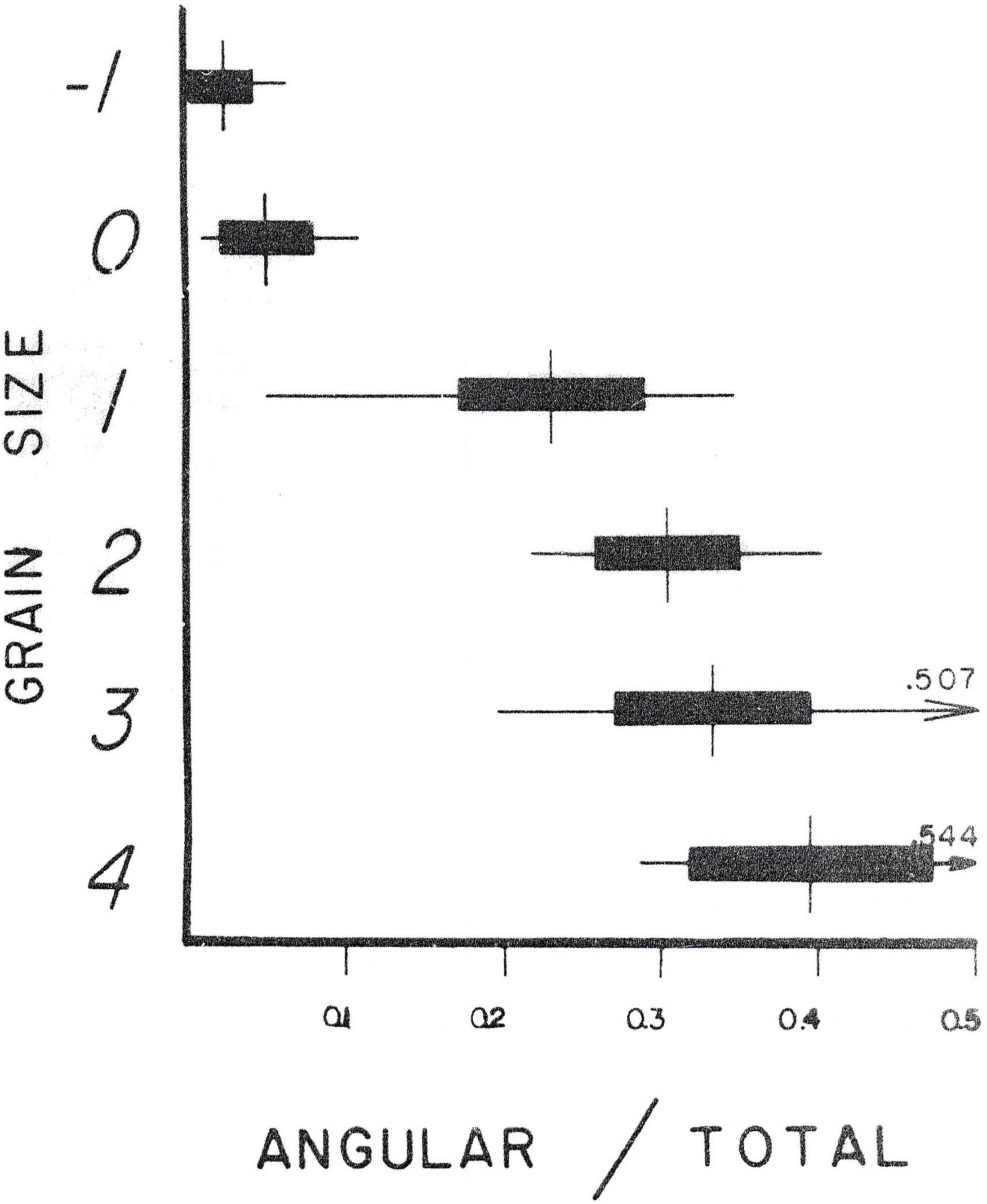

GRAIN SIZE
-1
0
1
2
3
4
.507
.544
0.1
0.2
0.3
0.4
0.5
ANGULAR / TOTAL

Fig. 17. Summary of feldspar/feldspar plus quartz ratios of the Little Missouri River sediments.

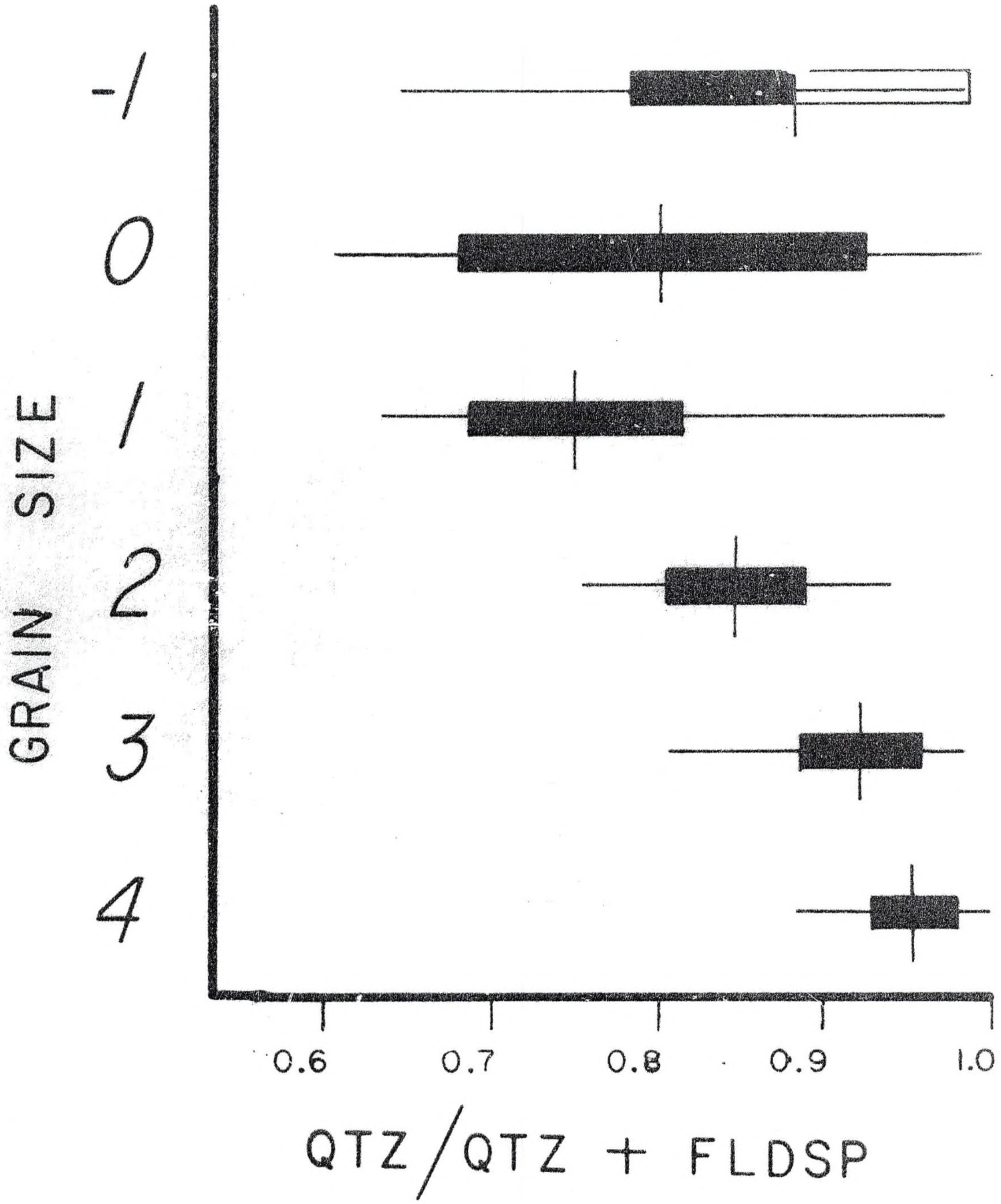

GRAIN SIZE
-1
0
1
2
3
4
0.6
0.7
0.8
0.9
1.0
QTZ/QTZ + FLDSP

Fig. 18. Cumulative frequency diagram showing the composition of the 2 phi size interval of each sample. Note that lack of systematic variation downstream, which seems to indicate that local source variation is more influential than fluvial processes in modifying sediment composition.

The results shown in Figures 15, 16, and 17 may be interpreted as a proof of the theory of terminal grain size. This theory, briefly, states that in a given system, mono-mineralic grains will be reduced to some characteristic size that is constant for the system; therefore, an estimate of the system's maturity may be gained by determining the proportion of grains that have been reduced to the terminal size. Actually, the grains are found to be distributed around the characteristic size. This theory has been applied to the study of glacial tills (Dremanis and Vagners 1971), and to the heavy mineral fractions of sedimentary rocks derived from various sources (Sindowski 1949).

Sindowski believes that the grain size distribution of minerals is a reflection of source rather than a result of mechanical abrasion. Dremanis and Vagners believe that a mineral grain that has reached its characteristic size cannot be reduced in size by further abrasion.

Gaudin (1926) crushed and ground quartz in a variety of machines. After several timed runs of quartz in a batch ball mill (Figure 19), Gaudin concluded that the output of any mill was a function of feed size, ball size, and method of operation (constant output or batch). This however, is moot; I can understand that a glacier may be analogous to a batch mill, but I do not believe the analogy can be applied to streams.

Sources of Error

One possible source of error in the weight percent data reported for the granulometric analysis is due to the presence of lignite in some of the samples. Lignite, where present, made up less than five percent of the sample volume, and was usually washed away during the sieving

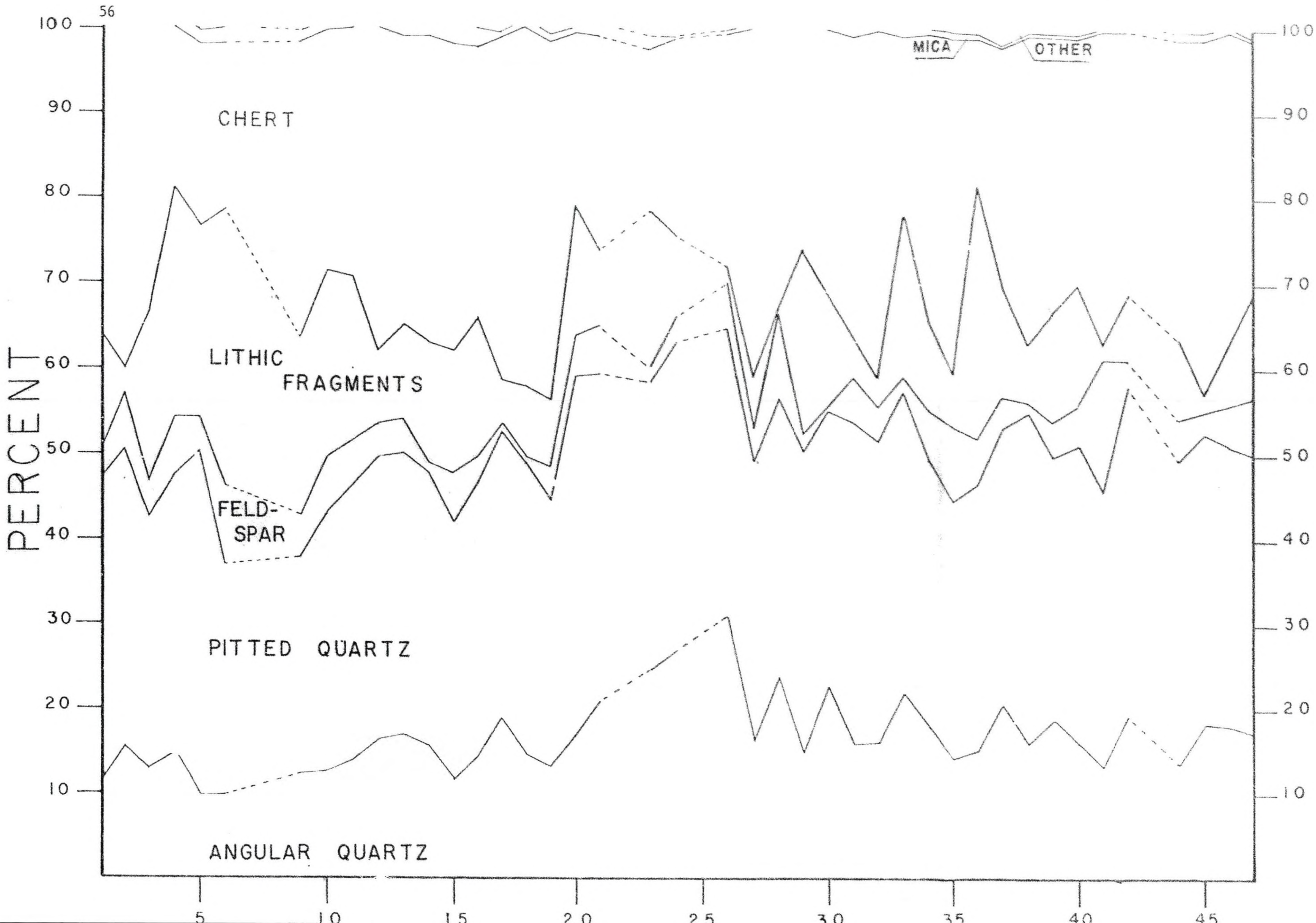
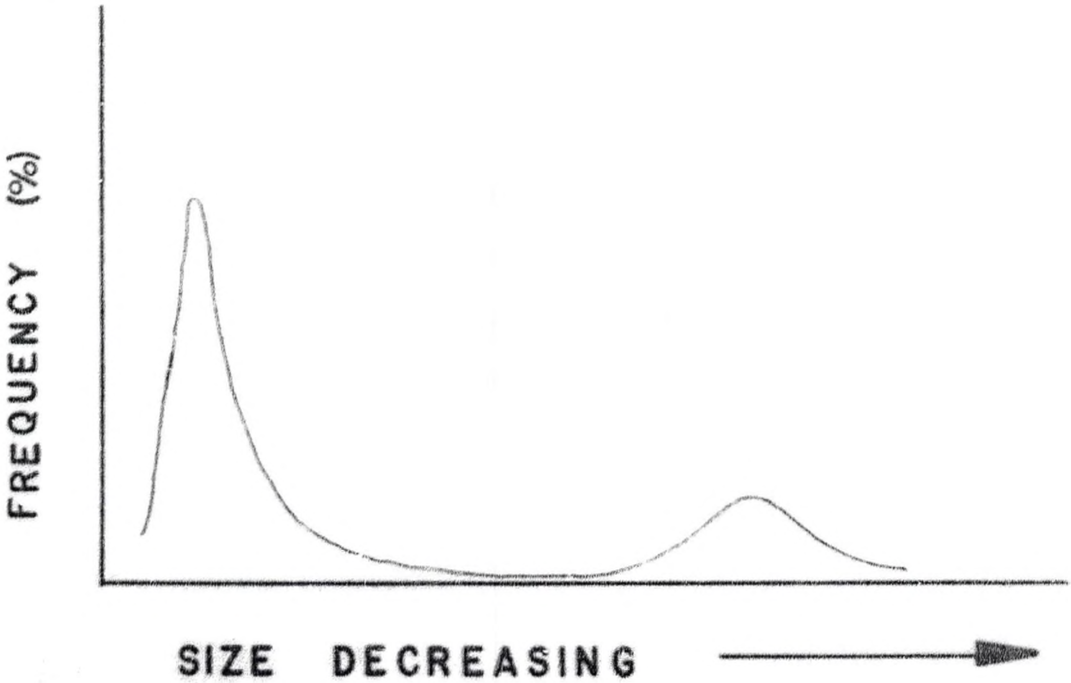
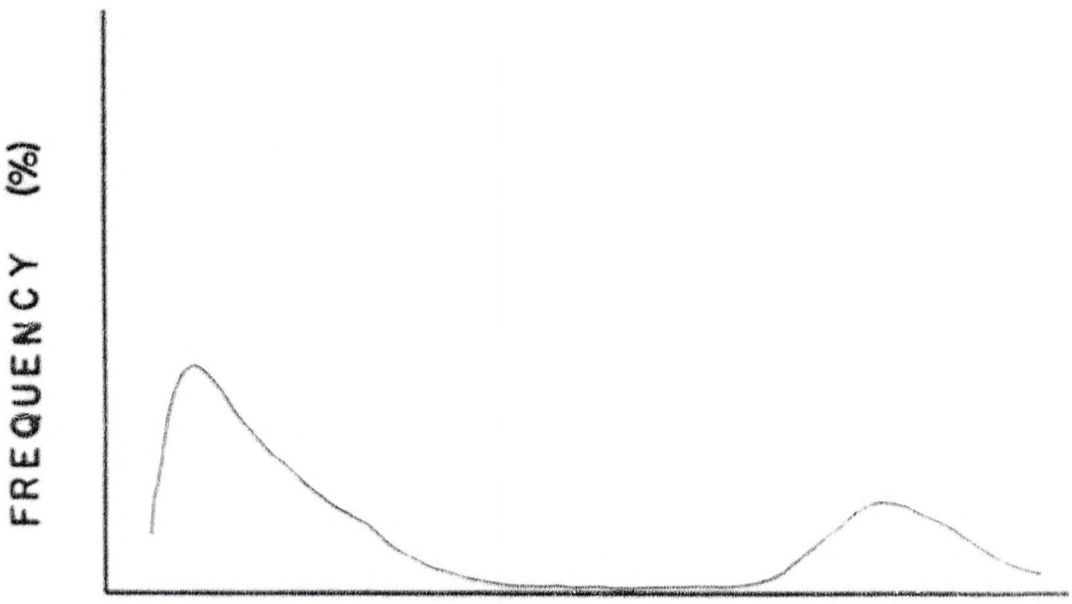

PERCENT
100
90
80
70
60
50
40
30
20
10
CHERT
MICA
OTHER
LITHIC
FRAGMENTS
FELD-
SPAR
PITTED QUARTZ
ANGULAR QUARTZ
5
10
15
20
25
30
35
40
45

Fig. 19. Frequency distribution of quartz particles after grinding in a batch ball mill (a, after 4 hours; b, after 16 hours). From Gaudin 1926. Left peak is centered on size of feed stock. Peak to right represents terminal size; but peak shifts further to r'ght as time of run is increased.

a



b



process. The specific gravity of lignite containing forty percent water is approximately 1.3 g/cm^3 (Hares 1928), and as the specific gravity of sediments is near 2.65 g/cm^3 (Garde and Ranga Raju 1977), the error is less than one percent.

The data which describe the sediment composition contain an error of unknown magnitude. The error arises from the difficulty of differentiating between clear, angular quartz and clear, angular feldspar, especially when the grains are smaller than three phi. Misidentification of these two minerals probably was random. Replication by counting several slides seems to indicate that the error is small and systematic, although the replications were too few to be statistically valid.

CONCLUSIONS

The Little Missouri River is a meandering stream with a highly variable discharge rate. The river channel becomes braided as it approaches Lake Sakakawea. The development of a braided channel may be a response to one or more of the following:

1. construction of the reservoir at Lake Sakakawea,
2. increased bank erodibility, or
3. water loss to the ground.

Further observation of the river should determine which of the above explanations is most likely.

The river is depositing medium to fine silty sand. The mean grain size of the sediments is coarser than the mean grain size of the formations exposed in the drainage basin, perhaps because the ephemeral tributaries of the Little Missouri River are usually located in local sand bodies which are more easily eroded than the silty or clayey beds. It is also possible that the presence of "scoria" among the lithic clasts increases the mean grain size. "Scoria" is a natural brick material produced by burning lignite, and crumbles into coarse fragments. These coarse fragments were silt and clay particles before the formation of scoria.

The mineralogic composition of the sediments varies with grain size. Coarse grains are most likely to be pitted quartz or lithic fragments while finer grains are usually chert, pitted quartz or angular quartz. Data that would allow speculation about the source

of the sediments are sparse, although there is no reason to suppose that the sediments are not derived from either the Bullion Creek or Sentinel Butte Formations through which the river flows for several hundred kilometers. Indeed, in mineralogic composition petrographically the sediments are very much like the sediments in the Bullion Creek Formation.

I did not find that any mineral alternately appeared and disappeared over the stream course, as noted by Cross (1976). I conclude that Cross was mistaken.

It appears that, at least in this river, several minerals are distributed according to size, in contradiction to the generally held view that only lithic fragments are distributed in a size-sensitive manner. The sediments have been sorted by size, and although the precise sorting mechanism is unknown, it is probable that the sorting mechanism will be described when transport processes are more fully understood.

Recommendations

I see little practical value in further studies of the sediments of the Little Missouri River. The scant data available concerning the mineralogy and petrology of the strata exposed in the drainage gasin hinder efforts to trace the sediments to their source(s), and there is small chance that the sediments will become valuable for any purpose in the future.

The one aspect of the river that may deserve further study is the change in channel habit, from meandering to braided.

APPENDICES

APPENDIX A

RESULTS OF GRANULOMETRIC ANALYSES

TABLE 3

RESULTS OF GRANULOMETRIC ANALYSES

Sample	Size Interval -2 φ	-1 φ	0 φ	1 φ	2 φ	3 φ	4 φ	>4 φ
1	0.1	0.1	0.1	1.0	33.8	60.8	4.2	1.0
2	3.8	2.8	17.4	45.3	19.9	4.8	2.2	3.8
3	7.6	8.6	24.2	35.4	11.2	8.3	3.2	1.5
4	1.3	4.6	15.8	50.7	17.6	6.2	2.3	1.4
5	2.5	1.2	5.0	12.0	20.5	49.6	7.4	1.8
6	0.9	2.1	8.0	28.2	42.9	15.7	1.8	0.4
7	1.1	4.6	25.9	57.1	9.8	0.9	0.4	0.2
8	40.6	14.9	20.1	18.1	2.7	1.9	1.0	0.7
9	3.2	3.2	8.1	21.0	50.4	12.8	0.9	0.4
10	0.3	1.0	5.5	15.5	33.7	38.4	4.2	1.4
11	1.6	4.2	13.9	29.2	41.6	8.3	0.4	0.8
12	1.3	7.1	18.1	27.5	34.2	11.0	0.2	0.6
13	22.6	34.6	49.9	73.1	94.9	99.2	99.6	0.4
14	5.2	13.3	20.7	39.2	87.1	97.7	99.4	1.6
15	4.7	7.9	13.9	30.7	83.6	97.7	99.1	0.9
16	3.8	5.9	10.4	25.8	81.9	97.1	98.7	1.3
17	0.9	1.3	2.4	5.9	28.4	76.3	93.5	6.5
18	2.4	5.3	21	71.7	91.6	99.4	99.9	0.1
19	1.1	4.5	20.8	67.6	86	98.9	99.7	0.2
20		0.3	0.7	2.1	7.8	33.7	35.7	43.6
21	3.1	9.9	26.1	49.9	71.5	88.2	93.6	6.4
22			0.1	0.3	0.7	1.4	4.8	95.2

TABLE 3--Continued

Sample	Size Interval -2 φ	-1 φ	0 φ	1 φ	2 φ	3 φ	4 φ	>4 φ
23	4.6	12.6	37.5	65.8	84.6	92.3	97.7	2.3
24	11.2	15.9	32.5	52.9	59	82	91.3	8.7
25	0.6	3.6	28.8	89.3	95.9	97.7	98.8	1.2
40				0.1	15.3	90.1	97.4	2.6
41					12.4	36.6	67.2	32.3
42					0.6	11	51.1	48.9
43								100
44			0.2	0.7	4.8	76.6	85.3	14.7
45				0.3	4.7	80.4	88.3	11.7
46			0.2	0.6	4.1	79.9	89.1	10.9
47			0.3	0.8	4.8	87.5	95.4	4.5

NOTE: All measurements in grams.

APPENDIX B

MINERALOGIC COMPOSITION OF THE SIZE INTERVALS

TABLE 4

MINERALOGIC COMPOSITION OF THE -1 ϕ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
3	1.0	38.0	2.3	53.3	5.3		
4	0.7	42.7	3.0	52.7	1.0		
7	0.3	50.7	2.7	45.3	1.0		
8		40.3	3.3	56.0			0.3
12	1.0	36.3	2.7	58.3	1.7		
13	0.3	35.0	5.3	57.3	1.7		0.3
14		37.7	2.3	59.3	0.7		
15	0.7	47.7	2.0	49.7	0.3		
19	0.7	37.0	5.3	54.0	2.3		0.7
21	3.0	42.3	7.3	45.3	2.3		
23	1.3	42.7	24.3	29.3	2.3		
24	2.3	39.7	4.7	54.3	0.7		
26	1.7	44.7	21.7	29.0	2.3		0.7
28	0.3	41.0	0.7	57.0	1.0		
Mean	1.0	41.1	6.3	50.1	1.5		0.1
Standard Deviation	0.9	4.4	7.3	9.8	1.4		0.3

TABLE 5

MINERALOGIC COMPOSITION OF THE 0 φ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feldspar	Lithic Frags	Chert	Mica	Other
2	2.0	32.3	1.3	57.0	7.0		[illegible].3
3	0.7	33.0	1.0	58.3	7.0		
4	0.7	39.7	2.0	52.0	5.7		
5	2.3	38.5	3.1	49.7	6.3		
6	1.7	40.1	5.4	48.1	4.3		0.3
7	1.9	53.6	3.1	38.7	2.7		
8	2.2	41.7	11.8	41.3	3.0		
9	3.2	29.0	8.3	55.5	4.1		
10	4.0	31.6	16.4	46.5	1.3		0.3
11	2.3	32.7	16.5	42.7	5.0		0.7
12	0.7	36.7	10.4	48.1	4.3		
13	2.0	30.2	15.6	47.0	5.3		
14	0.3	34.0	10.0	50.3	4.7		[illegible].7
15	1.3	55.7	3.7	37.3	1.7		[illegible].3
18	3.0	47.0	3.9	40.7	3.7		[illegible].7
19	0.7	39.3	17.7	40.7	1.7		
21	0.7	46.3	16.0	35.3	1.0		0.[illegible]
23	1.7	41.6	17.4	36.2	3.0		0.[illegible]
24	3.5	35.6	20.3	35.9	4.7		
25	2.4	4[illegible].2	20.5	27.6	8.3		
26	1.7	38.4	16.0	37.6	5.7		0.7

TABLE 5--Continued

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
28	2.0	46.9	0.3	50.0	0.7		
35	0.7	46.0	3.3	49.3	0.7		
36	0.7	15.5	7.8	60.3	14.5		1.3
Mean	1.8	39.5	11.2	46.3	4.6		0.3
Standard Deviation	1.1	8.5	8.5	8.5	3.6		0.5

TABLE 6

MINERALOGIC COMPOSITION OF THE 1 ϕ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
2	11.9	29.3	1.2	51.0	6.3		0.3
3	12.5	34.5	21.0	26.0	5.9		
4	9.4	39.8	18.2	28.2	4.4		
5	12.5	39.9	17.7	23.5	6.1	0.3	
6	13.7	38.4	19.8	22.5	5.7		
7	14.0	38.2	21.5	20.4	5.8		
8	10.4	37.3	20.9	28.2	3.1		
9	10.1	30.6	15.8	33.6	7.9		2.0
10	13.0	35.7	19.2	26.0	6.1		
11	9.3	41.0	18.8	25.5	4.8		0.7
12	18.7	41.0	19.7	13.7	17.0		
13	14.3	38.7	13.3	19.7	13.7		0.1
14	13.0	41.3	12.0	21.0	12.0	0.1	
15	12.3	39.7	17.3	26.0	4.3	0.3	
16	14.0	35.3	12.3	27.7	10.3	0.3	
17	10.3	33.0	13.0	26.0	15.3	1.7	0.7
18	5.7	30.7	10.0	12.0	20.7		1.0
19	8.3	35.3	15.7	36.7	4.0		
21	13.3	37.7	14.3	23.3	11.3		
23	17.0	31.3	4.3	30.3	16.3		0.7
24	9.3	37.0	19.3	27.7	6.3	0.3	

TABLE 6--Continued

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
25	2.3	43.0	20.3	27.0	8.7		
26	11.0	42.3	20.3	27.7	6.0		0.3
27	7.0	36.0	17.7	24.0	11.7		0.3
28	12.7	39.7	13.7	29.7	4.0	0.3	
33	13.3	37.7	13.0	21.0	14.3	0.3	
34	15.7	41.0	15.7	22.0	3.3		
35	12.0	35.3	17.7	30.0	3.7	1.3	
36	2.0	16.7	10.7	68.0	7.7	0.3	0.3
Mean	11.5	36.9	15.8	26.7	8.6	0.2	0.3
Standard Deviation	3.4	5.3	5.0	9.6	4.8	0.4	0.7

TABLE 7

MINERALOGIC COMPOSITION OF THE 2 φ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
1	13.7	39.0	8.7	12.7	25.7	0.3	
2	17.0	37.7	14.3	12.3	18.7		
3	13.7	39.0	10.7	22.7	14.3		0.3
4	14.0	42.0	11.7	12.7	19.7	0.3	
5	15.0	38.3	9.3	14.7	25.3	0.7	2.0
6	12.3	40.3	5.3	19.0	22.7		1.3
7	16.7	26.3	12.0	39.3	8.3	0.3	0.7
9	16.7	38.3	8.7	16.0	25.0	0.7	
10	14.3	29.0	6.3	22.0	28.7	0.7	0.3
11	20.0	29.7	8.0	19.7	25.7	0.3	1.0
12	19.0	34.3	5.3	17.0	24.3		
13	12.0	43.0	11.7	23.7	19.7		
14	13.0	45.7	7.0	13.3	21.0		
15	15.3	34.3	13.0	19.7	16.3	0.3	1.0
16	13.0	32.7	5.0	18.0	31.3	0.7	
17	14.7	23.7	7.3	17.0	38.3	2.0	
[illegible]	13.7	32.3	5.3	13.7	37.3	0.3	
19	14.3	34.0	11.3	26.0	13.0	0.3	1.0
20	18.7	46.3	12.7	6.3	14.3	0.3	1.0
21	16.[illegible]	38.[illegible]	9.7	9.0	[illegible]	[illegible]	0.3
23	13.3	32.7	6.7	30.0	30.0	0.3	
24	15.7	42.3	12.0	14.3	14.3	1.0	0.3

TABLE 7--Continued

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
25	13.0	30.3	14.7	19.3	20.3	0.3	2.0
26	21.3	36.3	7.0	11.7	22.3	0.3	1.0
27	19.3	33.7	10.3	16.0	20.3	0.3	
28	22.3	34.0	11.0	11.3	20.3	0.3	
29	12.3	40.3	5.0	28.3	14.0		
30	13.7	34.3	5.7	30.7	15.3	0.3	
33	20.3	33.0	9.0	13.0	22.7	1.7	0.3
34	21.0	36.3	11.3	16.0	15.0	0.3	
35	17.0	32.7	13.3	16.7	19.0	0.3	1.0
36	8.7	21.3	5.7	57.7	5.0	0.7	1.0
37	15.7	35.0	5.7	32.3	10.3	0.3	0.7
38	18.3	36.0	17.7	12.3	15.3		0.3
39	14.3	35.0	12.3	20.3	17.0	0.3	0.3
40	13.0	40.3	12.0	20.0	14.3	0.3	
41	14.3	44.7	13.7	14.7	12.3	0.3	
44	17.3	41.0	13.7	14.3	12.3	0.3	1.0
45	14.0	33.7	7.7	19.3	24.0	1.0	1.0
46	16.3	39.0	12.3	16.7	14.0	1.0	0.7
47	12.0	36.3	11.7	26.7	12.7	0.7	
Mean	15.5	36.0	9.8	19.4	19.7	0.4	0.5
Standard Deviation	3.0	5.5	3.3	9.1	7.3	0.4	0.6

TABLE 8

MINERALOGIC COMPOSITION OF THE 3 ϕ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
1	12.3	35.0	3.7	12.7	36.3		
2	16.0	35.0	6.5	2.9	40.1		
3	11.9	30.9	4.0	19.7	33.5		
4	13.8	33.5	6.9	26.9	18.9		
5	9.9	40.5	3.7	22.5	21.4	1.7	0.3
6	9.8	27.7	8.9	32.1	19.6	2.0	
9	12.5	26.4	3.9	21.0	34.5	1.3	0.3
10	12.7	30.2	6.2	21.9	28.3	0.7	
11	14.1	40.3	5.6	10.6	29.4		
12	16.3	33.3	3.7	8.7	38.0		
13	17.0	33.0	4.0	11.0	34.0	0.7	
14	15.7	32.0	1.3	14.0	36.0	1.0	
15	11.7	30.3	5.7	14.3	36.0	2.0	
16	14.3	32.3	3.0	16.4	36.6	2.4	
17	18.8	33.6	1.0	5.2	40.3	0.7	0.3
18	14.7	34.2	0.7	8.3	42.2		
19	13.3	31.3	4.0	7.7	42.0	1.0	0.7
20	17.0	42.0	4.7	15.3	20.3		0.7
21	21.0	38.3	5.7	[illegible]	25.3	0.7	0.3
23	24.7	33.7	1.7	18.3	19.0	1.7	1.0
24	27.0	36.0	3.0	9.3	23.0	0.3	1.3
26	31.0	33.7	5.3	2.0	27.3	0.3	0.3

TABLE 8--Continued

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
27	16.3	33.0	3.7	6.0	41.0		
28	23.7	32.7	10.0	0.3	32.7		0.7
29	15.0	35.3	2.0	21.7	26.0		
30	22.7	32.3	0.7	11.3	33.0		
31	16.0	37.7	5.3	15.7	24.3	0.3	0.7
32	16.3	35.0	4.0	3.7	40.7	0.3	
33	22.0	35.2	4.4	16.2	21.4		0.7
34	18.0	31.3	4.0	12.3	33.7		0.7
35	14.3	30.3	8.7	6.3	39.3	0.7	0.3
36	15.3	31.3	5.3	29.7	17.3	0.7	0.3
37	20.7	32.3	3.7	13.0	28.0	0.3	2.0
38	16.0	38.7	1.3	7.0	36.0	0.3	0.7
39	18.7	31.0	4.0	12.7	32.7		1.0
40	16.0	35.0	4.7	14.0	30.3		
41	13.3	42.3	5.3	2.0	36.0	0.3	0.7
42	19.3	38.7	3.0	7.7	31.0	0.3	
44	13.7	35.7	4.7	9.3	36.3	0.3	
45	18.3	34.0	2.7	2.0	41.7	1.0	0.3
46	18.0	33.0	4.7	7.0	37.0		0.3
47	17.3	32.7	6.7	11.7	30.3	0.3	1.0
Mean	17.6	34.9	4.5	12.9	32.2	0.5	0.3
Standard Deviation	4.9	4.8	2.2	8.5	7.0	0.7	0.5

TABLE 9

MINERALOGIC COMPOSITION OF THE 4 ϕ SIZE INTERVAL (%)

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
1	13.3	32.7	4.3	5.3	43.7		0.7
3	14.3	30.0	3.0	11.3	42.3	0.7	
5	22.7	27.0	1.0	17.7	31.0	0.7	
10	29.0	27.1	1.0	6.3	36.0	1.7	
17	17.0	32.0	2.7	4.3	42.7	1.3	
20	19.7	30.3	3.7	6.3	38.0	1.7	0.3
21	28.0	34.0	2.3	2.3	30.3	1.3	1.7
22	32.3	31.3	0.3	2.0	33.7	0.7	
23	30.7	25.7	0.7	12.3	29.3	1.0	0.3
24	32.0	33.0	4.3	1.7	27.7	0.7	0.7
26	29.0	31.0	2.7	6.3	30.3		0.7
28	27.3	29.0	4.3	2.7	35.7	1.0	
29	26.3	32.3	2.3	8.0	30.3	0.7	
30	19.0	30.3	3.0	6.7	41.0		
31	13.0	32.7	3.7	10.3	40.0	0.3	
32	22.7	29.7	1.0	3.3	43.3		
33	28.3	38.7	1.3	10.7	30.3	0.7	
34	22.7	33.0	3.3	9.7	29.0	0.7	0.7
35	18.0	29.0	2.7	7.7	42.0	0.3	0.3
36	23.3	34.3	0.7	10.3	30.3	0.3	0.7
37	16.3	31.0	6.3	6.7	37.3	1.7	0.7

TABLE 9--Continued

Sample	Angular Quartz	Pitted Quartz	Feld-spar	Lithic Frags	Chert	Mica	Other
38	17.3	34.7	6.0	2.7	39.0	0.3	
39	16.7	36.3	3.7	8.3	35.3	0.3	
40	13.3	31.3	0.7	11.0	43.3		
41	16.3	32.0	3.7	7.3	37.7	1.0	
42	24.3	33.7	0.7	4.0	35.0	1.0	1.3
44	18.7	29.7	2.3	5.3	44.0		
45	16.3	32.0	3.7	5.7	40.7	0.7	1.0
46	22.7	31.0	1.0	5.3	39.3	0.7	
47	14.7	34.0	2.0	7.0	42.3		
Mean	21.5	31.6	2.6	7.0	36.7	0.7	0.3
Standard Deviation	6.1	2.7	1.6	3.6	5.3	0.5	0.5

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