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SEDIMENTARY STRUCTURES AND PALEOCURRENTS IN A FLASHY CHANNEL

By

Kevin Bellamy
(B.E.S. University of Waterloo, 1976)

Submitted in partial fulfillment of
the Master of Arts Degree (Geography)
Wifrid Laurier University
1979.

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ABSTRACT

Highland Creek can be defined as a flashy stream on the basis of the basin and channel hydrology and hydraulics. The extremes between the low and high-flow stage are dependent on the hydro-geomorphological features of the urban environment. The peculiarities of the urban landscape, serve to differentiate Highland Creek from naturally flashy channels.

The sedimentary structures were grouped into coarse and fine facies. The deposition of material apparently occurs under progressively decreasing energy levels, during falling flow stage.

Bedform and sedimentary structure associations, and their evolution are dependent on the dynamics of the flashy channel. That is, the development of bedforms and associated features should be examined in view of the magnitude or intensity of interaction between the bed material and the flow. Small-scale bedforms may not fully develop, if the bed configuration does not achieve a balanced state with the flow conditions, especially under rapidly varied flow conditions. The evolution of bedform associations, and the recognition of such phenomena are readily identified with falling-flow stage. The small-scale bedforms are not preserved in the alluvium, with

the exception of bed armour. Parting lineations on ripples, ripples on channel bars, and channel bars on the channel form are recognized at low flow, although they are not preserved during subsequent events. Only the macroforms, as for example, point bars and riffle bars, are likely to be preserved because of their low sensitivity to short-term flow dynamics.

The analysis of paleocurrent directions suggested that the small-scale bed features and sedimentary structures were largely inefficient for modelling general flow directions. Sample vector resultants deviate significantly from the trends displayed by the channel and the valley. The hierarchical ranking of paleocurrent indicators was subdivided into two distinct groupings: a) a ranking of grand vector resultants with respect to the valley direction; and b) statistical ranking as derived from the comparison of concentration parameters (K) about the grand vector resultants of the sample groupings. The channel orientation is the best general paleocurrent indicator, since the vector resultant parallels the trend of the valley. Gravel fabrics and imbricates were combined to form the second order paleocurrent indicators. The grand resultants of the fabrics and the imbricates deviate by 17° from the parallel-to-flow direction of the valley and the channel. The small-scale sedimentary structures and bedforms are relatively inefficient paleocurrent indicators, since grand vector resultants deviate by 40° from the direction of the channel and the valley, as demonstrated by cross-strata and ripple orientations.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

A	cross-sectional area
Ac	accuracy index (semi-angle of confidence)
a	semi-angle of confidence for calculating optimal paleocurrent sample size
B	between-site population variance for paleocurrent indicators
d	average depth of flow
F	F statistic
Fr	Froude Number
K	precision estimate about the grand vector resultant
L	vector magnitude expressed as a percentage
l	Z-score value used in the calculation of K
m	weighted paleocurrent sample size
mi	actual paleocurrent sample sizes
N	Total number of paleocurrent observations in a sample grouping
n	Manning roughness coefficient number of paleocurrent sample sites
P	Rayleigh Test Probability
Q	discharge
Qs	bedload discharge
R	magnitude of grand vector resultant hydraulic radius
Re	Reynolds Number
Ri	Vector magnitude of vector resultants
r	semi-angle of confidence about the grand resultants
S	energy gradient
s	standard deviation about vector resultants
U	average flow velocity
U^*	shear velocity
W	within-site population variance for paleocurrent indicators
w	channel width
α	significance level for Z and F statistics
γ	specific weight of water
γ_s	specific weight of sediment
θ	vector resultant direction
ρ	dynamic density of water
σ	standard deviation (grain size)
τ	shear stress
ν	kinematic viscosity

GLOSSARY OF TERMS

Anabranch.- The term anabranch is used in this project to describe a minor channel that may occur between channel bars and the channel bank, or that may serve to dissect the surface of the bars. The anabranches typically transmit a lower volume of water than the main channel or Thalweg.

Flashy.- The term flashy is used to describe the recent hydraulic behaviour of Highland Creek, and to define the extremes that may occur between low and high flow. The term is meant to convey the notion that the changes in the severity of flow can occur rapidly, and to a high order of magnitude, during the course of a runoff generated flow event.

Macroform.- Macroforms consist of the largest-scale bed and channel features that can be identified in an alluvial channel. The features are relatively insensitive to the short duration dynamic events, and respond to the longer term hydro-geomorphic factors. Point and riffle bars, the channel form and the valley are considered to be macroforms.

Morpho-structural unit.- Morpho-structural units are large-scale bed or channel features that are formed of the lesser or smaller sedimentary structure assemblages. Point bars, as an example, are formed of a variety of features, such as cross-strata, plane-bedded, and so on.

Point bars.- The point bar is a macroform bed feature, and normally indicates the locus of deposition of sediment, along the convex bank of a channel bend.

Riffle bars.- Riffle bars are associated with riffle sequences that occur in channels. The riffle, especially in meandering or sinuous channels, marks the cross-over of the maximum thread of flow velocity, Riffles, in meandering rivers, are typically located immediately upstream of the bend apex, and are characterized by shallow flow depth, a wide section, and steep slope. The large-scale riffle bars are marked by erosion during low flow and deposition during high flow stage.

CHAPTER ONE

INTRODUCTION

The study of sedimentary structures and paleocurrent directions is an important facet of geomorphology and sedimentology, especially with respect to alluvial channels and paleohydraulic reconstruction.

Hydraulic engineers have contributed to the study of fluvial processes through the examination of fluid mechanics and sediment transportation. One of the most important results of such studies has been the detailed evaluation of bedforms and bedform mechanics. While the dependent and independent hydraulic variables of unidirectional flows have not been isolated from experiments or field studies, some conceptual models and relationships have evolved as exemplified , for example, by the work of Simons and Richardson (1961) on bedforms and flow regimes.

The study of sedimentary structures by geomorphologists and sedimentologists, in fluvial environments is dependent to a great extent on the concepts developed by hydraulic engineers. Sedimentary structures can in most cases be related to the erosion, transportation and sedimentation of alluvium. The difference between the study of bedforms and sedimentary structures is apparent, since in most cases bedforms are examined with respect to sediment movement in active fluid flows, whereas, the sedimentary structures are viewed as being the preserved formations attributed to specific bedforms, and are examined from an interpretative perspective.

In many cases the study of bedforms in alluvial channels is hampered by coarse bed material or variable flow conditions. In such instances the study of sedimentary structures may be the only means by which the hydraulic characteristics of a channel can be elucidated. Continuous flows are characterized by continuous sediment motion and hence some form of associated bedforms. Flashy channels can be shown to deviate from the continuous flow channels, since sediment movement may be all but restricted to the occurrence of high magnitude flows. In the absence of data acquired from flow extremes one must rely on the presence of preserved sedimentary features for paleohydraulic data.

Paleocurrent directions serve to elucidate the trajectories of flow in channels, when hydraulic data are absent. Thus, directional data can be used in combination with primary sedimentary structures to determine paleohydraulic conditions during dynamic events. Paleocurrent data are not independent of the structural features, since flow directions are obtained from the directional attributes of the sedimentary features.

The subsequent analysis is interpretative and is based on the extraction of information from existing sedimentological features in an alluvial channel. The most important phenomena to be studied are the sedimentary structures and paleocurrent directions. The key to the analysis is that the channel is flashy.

A Definition of a Flashy Channel

A flashy channel can be defined as being a river that is characterized by extremes between low flow minima and flood level maxima. The response to increases in discharge may be rapid or catastrophic as the result of inputs of runoff, as generated by rainfall or snowmelt. The combination of climatic and hydro-geomorphic phenomena contribute to the extremes that occur between flow minima and maxima.

Examples of flashy channels can be found in a variety of environmental situations. Ephemeral streams in arid regions typically respond catastrophically to large inputs of rainfall-generated runoff (Leopold and Miller, 1956; Picard and High, 1973). Braided rivers in glaciofluvial and alpine areas respond rapidly to snowmelt and glacial meltwater runoff (Collinson, 1970; Smith, 1971, 1974; Boothroyd and Ashley, 1975). Urban streams may likewise respond catastrophically to runoff input (Leopold, 1968; Gregory and Walling, 1976).

Purpose and Approach

The purpose of the project is to examine the nature of the sedimentary structures and paleocurrent directions in Highland Creek, as formed by recent high flow events. The study of the sedimentological properties of the contemporary channel can be used to determine the processes responsible for the sedimentary features, and can also be used in studies on paleohydraulic reconstruction in relict fluvial environments.

The initial portion of the study is devoted to a brief summary and discussion of available sedimentological data on flashy channels. The weaknesses of available data and the conceptual basis for this project are also defined in detail.

The most important segments of the analysis are devoted to the description and discussion of sedimentary structures and paleocurrent directions as they occur in Highland Creek. The latter sections are devoted to the analysis of the results and a sedimentological model of flashy channels.

Study Site Selection

The emphasis of this project relies on the analysis of the sedimentological attributes relating to flashy flow events. As noted above, flashy streams can be identified in several environmental situations. The stream chosen for the study is that of Highland Creek, Scarborough, Ontario, and is representative of an urban stream.

The environmental controls, in terms of climatic and hydro-geomorphic factors are largely of natural origin in the instance of ephemeral streams in arid regions and of braided channels in glaciofluvial or alpine areas. While the author cannot deny the importance of climatic and hydro-geomorphic factors in determining the hydrological and hydraulic peculiarities of Highland Creek, it is obvious that the morphological features of the urban landscape deviate significantly from that of a natural situation. Thus, one need not venture into natural areas to examine the flashiness of an alluvial channel. It is because of the nature of the controls on Highland Creek that the system was chosen for study.

A second reason for the choice of Highland Creek stems from the availability of hydro-geomorphic data. The publication of recorded precipitation and stream discharge, and the hydro-geomorphological analysis of Neuhold (1975) provided the initial basis and stimulus for the study. Without such information, the project could not have been completed given the limitations imposed by time.

The author elected to restrict the length of the study reach of Highland Creek to about 600m. The extensive occurrence of channel controls precluded the use of longer segments at most channel locations. Furthermore, the relatively short reach enabled the author to extract the greatest amount of information given the restrictions imposed by time.

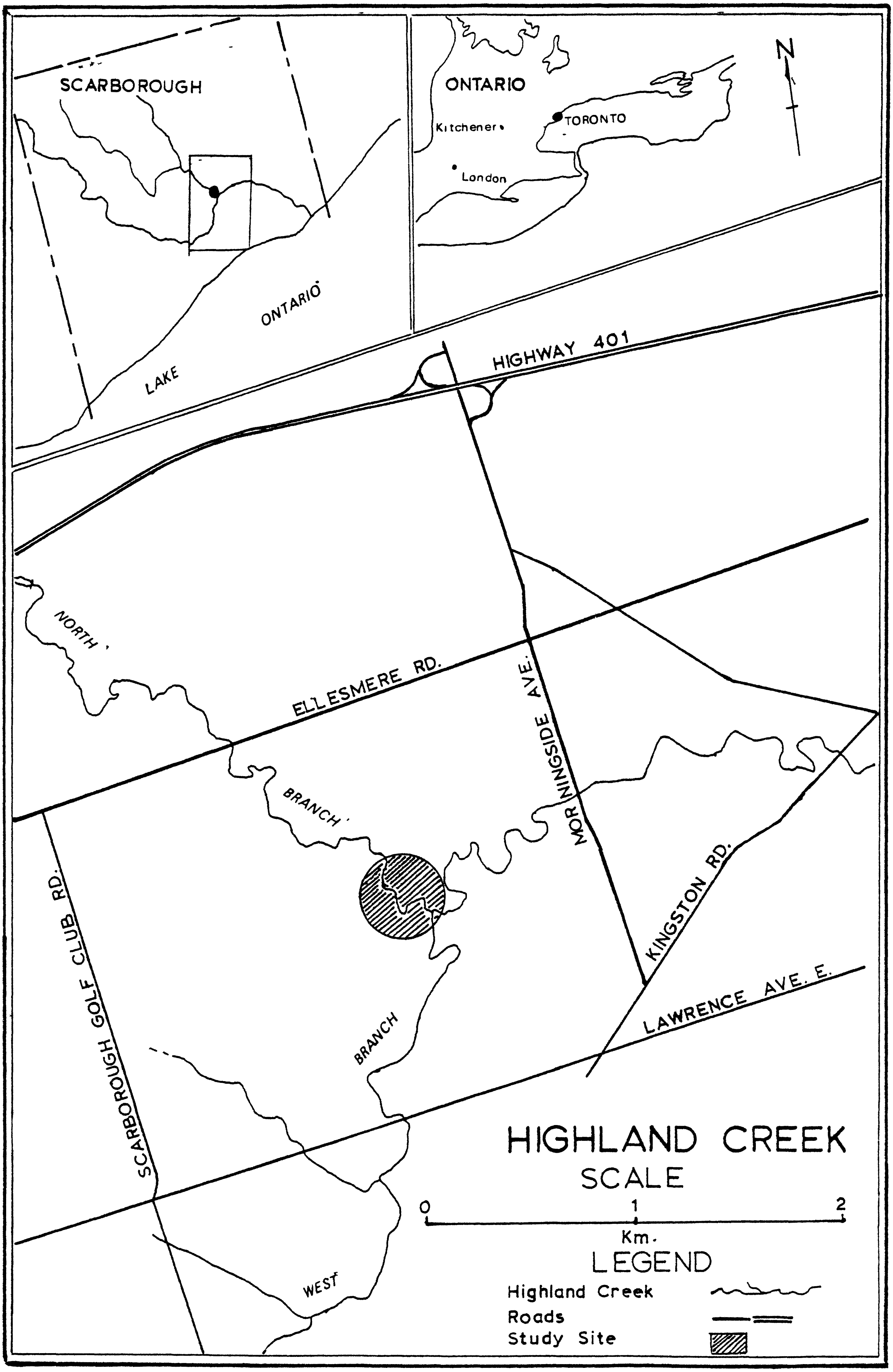
General Setting

Site Location. - As noted above, the selected study reach consists of a 600m segment of Highland Creek. The study site is located on the North Branch of Highland Creek at Morningside Park, Scarborough, Ontario (Figure 1). The site is accessible through Morningside Park, from Morningside Avenue. The author obtained additional morpho-structural data from additional locations on the West Branch, South of Lawrence Avenue East and East of Scarborough Golf Club Road.

Physiographic and Geologic Considerations. - Topographically, the Scarborough area consists of a broad crest of high land projecting southward from an elevated plain located north of Toronto, Ontario. The highest elevation of the area is 215m a.s.l., near Unionville. The surface slopes gently southward and eastward to the Lake Iroquois shore bluffs (140m to 200m a.s.l.) (Chapman and Putnam, 1966).

The surficial materials of Scarborough, and indeed all of Southern Ontario, consist of various stratigraphic sequences of glacial, glaciofluvial and glaciolacustrine sediments. The sedimentary deposits in the Highland Creek area also include glaciodeltaic and beach material from the Lake Iroquois sequences (Karrow, 1967).

FIGURE 1


SCARBOROUGH
ONTARIO
Kitchener
TORONTO
London
N
LAKE
ONTARIO
HIGHWAY 401
NORTH
BRANCH
ELLESMERE RD.
MORNINGSIDE AVE.
KINGSTON RD.
SCARBOROUGH GOLF CLUB RD.
LAWRENCE AVE. E.
BRANCH
WEST
HIGHLAND CREEK
SCALE
0
1
2
Km.
LEGEND
Highland Creek
Roads
Study Site

Highland Creek drains an area of 90 km^2 with a cumulative channel length of about 100 km. The channel slope is 0.0061. The total drainage basin area is located within the boundaries of Scarborough.

CHAPTER TWO

HYDROLOGY, HYDRAULICS, AND SEDIMENTOLOGY OF FLASHY CHANNELS

The prime objective of this project is to examine the nature of sedimentary structures and paleocurrent directions in Highland Creek, as formed by recent high magnitude flow events.

The most important data that may be used to define a flashy channel and to distinguish it from continuous flows are based on basin and channel hydrology and hydraulics. Such criteria have been alluded to, but not discussed or described in detail, in previous works. The data on Highland Creek as derived from recorded precipitation, discharge, and hydraulic characteristics serve to illustrate the peculiarities of a flashy channel. The data demonstrate the extremes between low flow and high magnitude flows.

The utility of sedimentological data for establishing commonalities associated with flashy channels, as contrasted with that obtained from continuous flows is uncertain at the present. The nature of the bedforms and sedimentary structures do not appear to parallel the trends that may be obvious from hydrological or hydraulic data. The reasons for such a problem are not self-evident. In the past the focus of sedimentological studies has been that of the study of primary sedimentary structures, bedforms, and to a lesser degree, paleocurrent and paleogeographic reconstruction. The result has been the documentation of various sedimentological features for various fluvial environments, and their hydrodynamic interpretation. A further outgrowth has been the formulation of tentative bedform associations and paleocurrent hierarchies. The bedform hierarchies of Allen (1968b, 1968c) have been tested against field data by Collinson (1970) and Jackson (1975b) with some success. However, questions arise about the applicability of such sedimentological models and their value in assessing all fluvial networks in a general sense. The wide variety of bedform and sedimentary structure types have been described and confirmed. Several questions can be derived from the analysis of sedimentary structures, bedform associations and paleocurrent directions. Can bedform associations and their preservation in flashy channel environments be expected to: a) evolve; and b) be preserved? Are the rankings of paleocurrent indicators realistic? Do all apparent paleocurrent indicators provide generalized information on paleoflow directions?

The above questions are representative of a small sample of problems that need to be solved. The data on sedimentary structures may yield information that can be used to distinguish flashy channels from continuous flow streams. The value of paleocurrent analysis, and the utility of the results is a problem that is not easily resolved. Too few sedimentological studies have resorted to the analysis of directional data in an attempt to assess the variance of paleocurrent directions, and the efficiency of indicators for modelling paleoflow directions. Because of the relatively ineffective use of paleocurrent data by many workers, it is difficult to formulate hierarchies of paleocurrent indicators at the present time.

The subsequent discussion in this chapter is aimed at an illustration of the hydrology and hydraulic characteristics with the use of data from Highland Creek. The latter sections are devoted to a summary and discussion of available sedimentological data on apparently flashy channels. Some of the problems associated with the sedimentology of alluvial channels forms the basis for the main objective of this study.

Hydrological Considerations

The accompanying hydrograpgh (Figure 2) is a plot of daily precipitation (Atmospheric Environment, and Meteorological Branch, Fisheries and Environment Canada), and daily mean discharge (Water Survey of Canada, Fisheries and Environment Canada) for May and June, 1977. Similar trends characterize the hydrographs for the other months. The records for 1978 have not been included because of the interruptions in the recorded discharge data, and also because of the dry weather and sustained low flow levels.

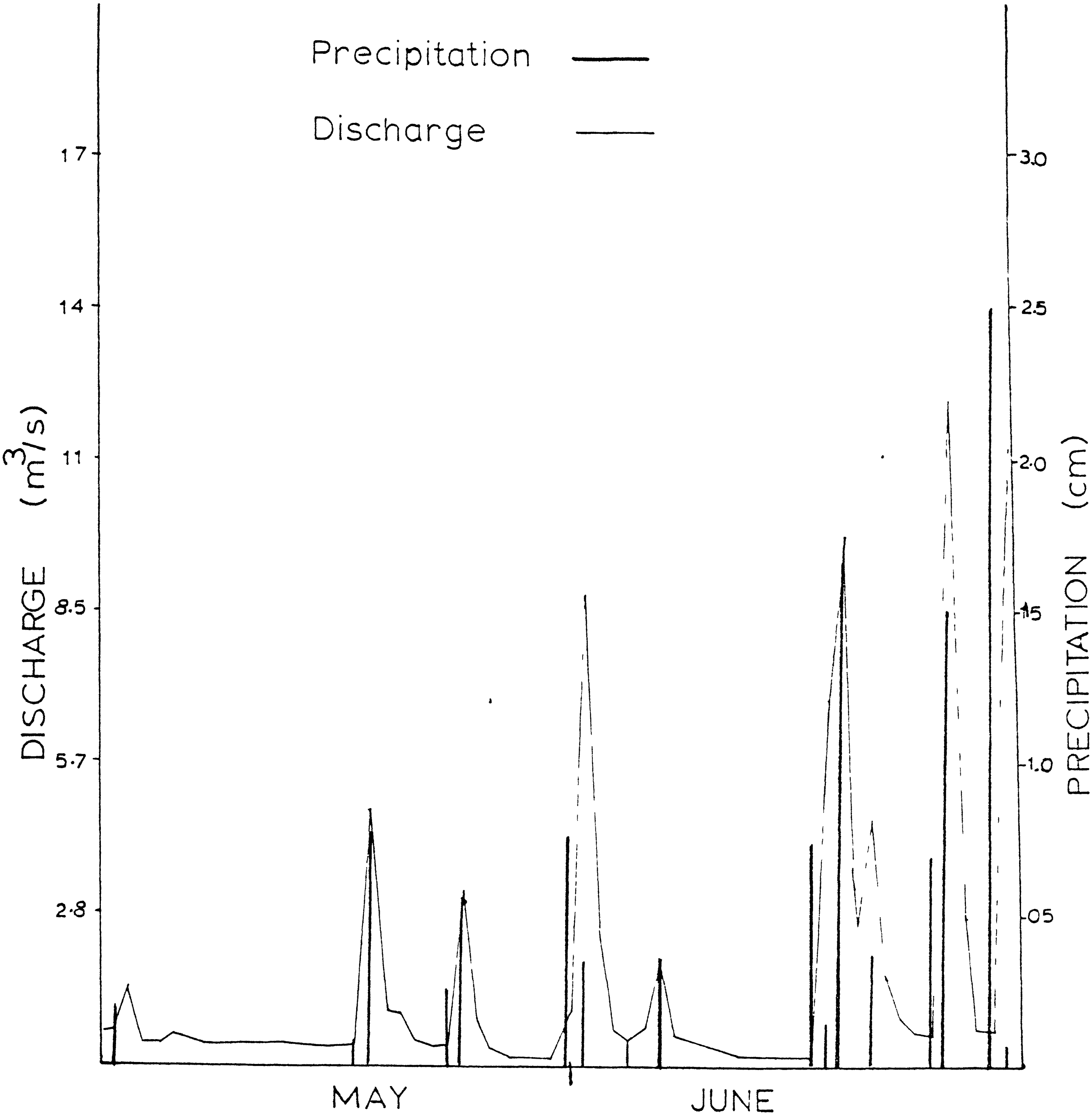
The hydrograph has been included to provide the reader with an indication of the extremes that occur between low flow levels and high magnitude flows that have exceeded $14m^3$/sec. The reader will also note the close association between the occurrence of rainfall and discharge peaks. It is impossible however, to determine the lag time between the start of rainfall and the initial phases of rising-flow stage. The hydrological data as shown,

FIGURE 2

HYDROGRAPH OF DAILY PRECIPITATION AND DAILY MEAN DISCHARGE

(MAY AND JUNE 1977)

(Data on Highland Creek show similar trends for all months)



serves to illustrate the flashy nature of the Highland Creek channel. It has been inferred that the intensity of the fluvial processes is directly related to the occurrence of runoff induced flow events.

The urban environment and the process of urbanization are largely responsible for the hydrological and hydraulic peculiarities of the Highland Creek channel (Neuhold, 1975). The land surface of the Scarborough area differs from the situation of natural vegetation and/or soil, since the paved roads, and buildings are impervious. As a result, the amount of surface runoff available to the channel is increased over that of the natural condition. Such statements can be substantiated by the brief comments of Gregory and Walling (1976). Vanoni (1975) stated that the erosive energy of a stream is a function of the water volume and its energy. When the volume of water is increased or is concentrated in natural or artificial channels, the erosive energy is increased substantially (four fold increases have been demonstrated by Wolman, 1967). The clearing of land will increase the percentage of rainfall that contributes to runoff. The alluvial channels simply concentrate the volume of runoff flow. From these arguments one can infer that the generation of runoff, and the concentration of flow in Highland Creek will be a definite factor in determining the intensity/magnitude of the fluvial processes.

As noted above, the urban landscape contrasts with that of the naturally vegetated surface. The soil surface, in nature, is not impervious and the total percentage of surface runoff generated by rainfall is relatively low. The vegetation helps to protect the soil by limiting or preventing splash and sheet erosion (Tricart and Cailleux, 1972), and helps to maintain a loosely packed soil structure. Therefore, the water supplied by rainfall largely contributes to ground water recharge, via infiltration. In addition, the infiltration of water in the presence of natural vegetation increases the lag time between rainfall and the initiation of the rising flow stage, reduces the magnitude of the discharge levels, and extends the higher flow levels over longer periods of time, as illustrated by Gregory and Walling (1976). As a result, the potentially destructive flows are reduced in frequency and magnitude (Morisawa, 1968). Leopold (1968) stated that the frequency of occurrence of high magnitude flows, or flooding, in urban areas, may be four times greater than that which may be expected in rural areas.

The hydrological data for Highland Creek may demonstrate the typical response of flashy channels to large inputs of runoff or meltwater, regardless of the general environmental setting of the alluvial channels. It is apparent that one need not venture into arid, alpine or arctic environments in order to observe the peculiarities of the flashy channel. Highland Creek is an urban stream, and is flashy as a result of man-induced phenomena. The cultural impact on Highland Creek contrasts with the environmental conditions associated with the aforementioned, natural channel types.

Hydraulics of Flow in Highland Creek

Throughout the summer and fall of 1978, the author measured and recorded the geometric and hydraulic variables at low flow levels, at four cross-sections within the study site. High magnitude flow events did not occur during the field season, and therefore, estimates of the high flow hydraulic geometry and flow velocity were made.

Collection of Low Flow Data.- Width measurements were obtained with a Lufkin 15m surveyor's tape. Depth values were taken at regular intervals across each section by way of a meter stick. Velocity determinations were made by standard methods with the use of a Teledyne-Gurley current meter. The discharge of water through each section was determined from the product of average width, average depth and average velocity in the form of

$$Q = UA \quad (1)$$

where

Q = discharge (m^3/s)
U = average velocity (m/s)
A = cross-sectional area (m^2)

Table I is a summary of the measured data for one sample. Other sets of data yielded comparable results. Table II is a summary of hydraulic variables derived from the data of Table I and additional physical properties of the channel segment. (Individual variables and their derivations are defined in Appendix I).

The low discharge levels in Table I are less than the base flow levels ($0.57 m^3/sec$) as derived from Figure 2. The dry weather and the fact that the North Branch contributes 40 per cent of low flow discharges, account for the discrepancy.

The last column of Table II indicates that the discharge of bedload material is zero as determined from the Meyer-Peter and Müller (1948) bedload function. The actual computations resulted in negative bedload discharge. Simons and Şentürk (1977) have stated that such a result is to be expected where bedload discharge is zero.

TABLE I

Hydraulic Geometry and Discharge

Section	w(m)	d(m)	U(m/s)	Q(m^3/s)
A-A	8.53	0.14	0.084	0.1003
2-2	7.01	0.26	0.057	0.1039
B-B	2.19	0.22	0.213	0.1026
C-C	4.47	0.17	0.277	0.2105

The data are representative of the hydraulic conditions and channel geometry for one set of measurements. Similar results were obtained from other times. The increased discharge from B-B to C-C is attributable to a storm sewer that enters the system between the two sections. The variables are: average width (w); average depth (d); average flow velocity (U); and discharge (Q). (All units are metric).

TABLE II

Hydraulic Conditions of Low Flow

Section	Fr	Re	S	n	τ	U*	Qs
A-A	0.0717	11,760	0.00006	0.025	0.0000087	0.0092	----
2-2	0.0357	14,820	0.00001	0.021	0.0000025	0.0049	----
B-B	0.1450	46,860	0.00004	0.011	0.0000085	0.0091	----
C-C	0.2145	47,090	0.00010	0.011	0.0000173	0.0130	----

The data presented above illustrates the hydraulic conditions of flow as determined for August 19, 1978. The values are representative of averages across each section, for the Froude Number (Fr), Reynolds Number (Re), energy gradient (S), Manning roughness coeffient (n), shear stress (τ), shear velocity (U*), and sediment discharge as bedload (Qs). The bedload discharge was derived from the Meyer-Peter and Müller (1948) bedload function. (All variables and their derivations are defined in Appendix I).

The zero bedload transport level at low flow stage is not indicative of the total sediment load. Neuhold (1975) demonstrated that small quantities of suspended and solution material are transported in concentrations of 0.10gm/l or less.

Paleohydraulic Reconstruction of High Flow Stage

In the absence of directly acquired field data, on high flow or flood stage conditions, the author relied on estimates of the hydraulic geometry and flow velocity to provide a contrast to the low flow stage conditions.

The methods employed are only approximate and probably do not yield reliable or accurate data. However, in the absence of more suitable means, the estimates are reflections of the best method available.

Approach. - The width of the high flow stage channel was assumed to be equivalent to the distance between bank-crests, across a section. The depth of the channel in the vertical profile is based on the difference in elevation between the channel bed and bank-crest. Velocities were approximated by two different methods for comparative purposes: competency estimates of Hjulström (1935) as based on the average bed material size; and by utilizing the maximum bankfull discharge levels (about 11.0m^3/s to

$20.0 m^3/s$) as extrapolated from Figure 2 and the study by Neuhold (1975). The estimated velocities compare quite well for both methods. The data is summarized in Table III.

As a check for the bedload computations in Table III, the author estimated the bedload discharge rate, through the section at A-A, by using the volume of material contained in the point bar.

Given the physical dimensions of the point bar at A-A, 15 m by 10m by 0.4m, the average specific weight of the sediment, 2.65 T/m^3, and an estimated porosity of 40 per cent, the sediment has a weight of 95.4 T. If one further assumes that the duration of an event is about six hours, then the transport rate is 0.0084 t/sec. The volumetric estimate, while somewhat less than the Meyer-Peter and Müller (1946) bedload computation, is comparable in terms of order of magnitude.

Discussion of the Hydrologic and Hydraulic Data

The data presented above provides the reader with a definition of a flashy channel. Highland Creek as a field example displays flashy characteristics as defined by the hydrology and hydraulics of the channel and the study reach,

TABLE III

Hydraulic Geometry and Sediment Discharge For High Flow Stage

Section	w	d	U	Q	Qs
A-A	19.1	1.50	0.489	14.00	0.00936
2-2	10.5	1.50	0.889	14.00	0.00550
B-B	18.6	1.00	0.753	14.00	0.00260
C-C	7.0	1.73	1.156	14.00	0.01100

The data utilized in the table has been based on the approximation of the bankfull channel geometry, and the discharge estimates of Neuhold (1975), for bankfull flow levels. The sediment discharge (Qs) is an estimate of the bedload discharge. The vaiables are: width (w); average depth (d); average velocity (U); discharge (Q); and bedload discharge (Qs). The variables required in the computations of bedload discharge, are deffned in Appendix I.

respectively. More important, the data demonstrates the wide extremes that can occur between base flow and bank-full or flood stages as a function of rainfall-generated runoff. The occurrence of high magnitude flows in Highland Creek is dependent on the occurrence of rainfall and probably snowmelt runoff, and most important, on the impact that the urban environment has had on the flow characteristics of the channel.

The hydraulic data, including the estimates of high magnitude flows, closely resembles the patterns illustrated by the hydrograph in Figure 2.

The discharge of sediment as bedload is expected to be the most important aspect of sediment conveyance in Highland Creek, as will be demonstrated, since it has been inferred from the examination of field data that the most important phases of sedimentation are related to the occurrence of high magnitude flow events and bed-load transport. The zero bedload transport levels of low-flow stage indicate that such flows are unable to transport the coarse bed material.

Finally, the environmental situation of Highland Creek is not necessarily unique, although the impact of the urban area on the channel clearly serves to differentiate natural flashy channels from those of cultural landscapes.

The Sedimentology of Flashy Channels

The preceding illustration of flashy flow conditions, as derived from Highland Creek, is important to the study of the sedimentology of the channel. The relationship stems from the patterns of sediment transportation that have been demonstrated by the hydraulic data. That is, the transport of bed material is restricted to the occurrence of a dynamic event. The movement of sediment is not restricted entirely to the most extreme flow conditions. It is here suggested that sediment transport rates range from trace levels of suspended and solution load at base-flow levels to maximum rates of sediment movement at bankfull to flood level discharges.

From the initial field survey it has been inferred that the most important phases of sedimentation are related to the occurrence of high magnitude flow events. Therefore, the sedimentary structures found in the channel deposits should reflect such a trend.

Picard and High (1973) have indicated that sediment erosion, transportation, and deposition are restricted to the occurrence of runoff-generated flows in ephemeral streams. The seasonal flooding that is normally associated with braided streams in alpine, glaciofluvial and other

TABLE IV

A Summary Of The Sedimentological Data on Flashy Channels

Author(s).	Environment and Flow Characteristics.
Doeglas (1962) (France)	Braided, periodic high flow
Collinson (1970) (Distal glaciofluvial Norway)	Braided, seasonal flood
McGowen and Garner (1970) (South, U.S.A.)	? , sinuous, flashy- periodic flooding
Bluck (1971) (Scotland)	Meandering, continuous flow, occasional flood
Smith (1971) (Mid-West, U.S.A.)	Braided,seasonal flooding
Picard and High (1973) (South-West, U.S.A.)	Ephemeral (braided), periodic flood due to storm runoff
Smith (1974) (British Columbia , Can)	Braided, (alpine), seasonal flood.
Jackson (1975b, 1976) (Wabash R., U.S.A)	Meandering, continuous flow occasional flood
Boothroyd and Ashley (1975), (Alaska, U.S.A)	Braided, glaciofluvial outwash, seasonal flood
Church and Gilbert (1975) (General)	? , general content on glaciofluvial- braided channels seasonal flood.
Clague (1975) (British Columbia, Can.)	Relict Pleistocene outwash, (seasonal flooding ?)
Gustavson, Ashley, and Boothroyd (1975) (Alaska, U.S.A.)	Glaciodeltaic, seasonal flow
Rust (1975) (Yukon, Can.)	Glaciofluvial outwash-Pleistocene, (probably braided, seasonal flood)
Hein and Walker (1977) (British Columbia, Can.)	Braided (alpine), seasonal flood

The data specified in Table IV, serves to illustrate the information that is available on flashy streams, in summary form. (The symbols are defined on each page, where they occur).

TABLE IV (cont'd)

Sedimentary Structures								
Gp	Gc	Gm	Og	Isg	Sp	Ssh	Sc	Csg
x	?	x	-	-	x	?	-	-
-	-	-	-	-	x	-	x	?
x	x	x	-	-	x	x	-	?
?	x	-	-	x	?	-	x	x
x	-	x	?	-	x	-	-	-
x	-	x (graded)	-	-	x	x	x	x
x	x	x	x	-	-	-	-	-
-	-	-	-	-	-	-	x	-
-	-	?	-	x	x	-	x (ripples)	?
x	x	x	-	-	-	-	x	-
x	x	-	-	-	-	-	x (ripples)	-
x	x (rare)	?	-	-	-	-	?	-
x	-	x	-	-	-	-	-	-
x	x	x	x	-	-	-	-	-

Gp - plane-bedded gravel
Gc - cross-bedded gravel
Gm - massive gravel
Og - open-work gravel
Isg- interbedded sand and gravel.
x - observed and documented
? - observation unknown
- - not documented

Sp - horizontal lamination
Ssh - subhorizontal lamination
Sc - cross-lamination
Csg - cross-laminae of sand and gravel

TABLE IV (cont'd)

Bed Material	Bedform Associations (Superpositions)	Paleocurrent Indicators
gravel with sand	----	fabrics
gravel with sand	r+d, r+Li, r+Sb, A+IB, d+Li, Lb+Sb	----
gravel with sand	r+Tb	----
sand with gravel	r+Mr	composite samples of cross-strata
sand and gravel	r+d, r+Lb/Tb, d+Lb/Tb	
sand with gravel	----	descriptive, no data
gravel	----	measures of flow directions
sand	r+d, r+Sw, r+Tb, r+PtB, d+Sw, d+PtB, Tb+PtB	cross-strata
sand and gravel	----	fabric
gravel	----	----
gravel and sand	----	----
sand and gravel	----	delta front orientations
gravel	----	fabrics
gravel	----	----

r - ripples
d - dunes
A - alternate bar
Li - linguoid bar
IB - island bar
Sb - side bar
Mr - mega-ripple
Rb - transverse bar
Lb - longitudinal bar
PtB - point bar

environments is closely linked to the phases of maximum sediment transport rates and deposition (Doeglas, 1962; Collinson, 1970; Smith, 1971, 1974; Boothroyd and Ashley, 1975; Hein and Walker, 1977). The above examples serve to illustrate that the most important phases of sedimentation are apparently linked with high magnitude flows, in flashy channels.

Some of the sedimentological data that is available has been summarized in Table IV. For comparative purposes, the author has included data on two continuous flow channels.

Explanation of the Sedimentological Data

Environment and Characteristics of Flow.- The first subheading in Table IV serves to demonstrate the variability of environmental situations that may be associated with flashy channels. Most of the documented streams are braided channels in glaciofluvial and alpine environments. In all cases the braided streams are characterized by multiple channels, and seasonal flooding. Typically, the seasonal flood corresponds to the release of meltwater from snow or ice during the melt-season. Smith (1971, 1974) has indicated that the seasonal high flow stages may fluctuate on a diurnal, weekly or longer term basis. Boothroyd and Ashley (1975) found that diurnal fluctuations in flow were not encountered on Alaskan outwash plains.

All of the studies of braided channels focused on upstream or proximal zones, with the exception of Collinson (1970), who concentrated on distal environments.

The ephemeral channels documented by Picard and High (1973) are characterized by dry channels and periodic flooding.

The continuous flow channels are meandering streams (Bluck, 1971; Jackson, 1975a, 1975b, 1976). The average discharge levels are occasionally interrupted by flooding.

The flashy channels that have been examined by McGowen and Garner (1970) are difficult to classify as they have indicated that in both cases the channels were sinuous (a sinuosity ratio of 1.5-1.7 on average). The authors did not specify whether the channels were at all braided, although they indicated the predominance of gravel sediment and bedload transport. Miall (1977) has grouped the study of McGowen and Garner with the data on braided channels in his summary.

The study of Gustavson, Ashley, and Boothroyd (1975) focuses on glaciodeltaic sediments in modern and relict environments. The flow characteristics are the same as for the braided glaciofluvial channels.

Sedimentary Structures. - The sedimentary structures illustrated in Table IV have been identified in the facies found at the Highland Creek site. The author has provided the data as a comparison with the Highland Creek examples. The features listed, as encountered in the field by others, can be associated with flashy or continuous flows. The variety of occurrence, and the lack of obvious trends makes it difficult, if not impossible, to distinguish between the sedimentary environments.

In many cases the absence of coarse or fine materials in large quantities may preclude the development of some facies. This problem further complicates the evaluation of sedimentological trends as associated with flashy and continuous flows.

The lack of documentation of some features may be the result of the non-occurrence of some facies, or else because the focal point of the discussions was not related to the identification of some facies. Terminological variations further hampers the evaluation of some features.

From available structural data it is very difficult to associate specific facies with either flashy or continuous flows. The sedimentary structures examined by Picard and

High (1973) are very similar, in some cases, with those of Highland Creek. Of significant importance are the fine facies, as the various forms of laminated fine sediment have been found in ephemeral streams by Picard and High and in Highland Creek, by the present author. The coarse facies of Highland Creek are more like the gravel structures defined by Smith (1974) for braided channels.

Associations of Bedforms. - The listing of superimposed bedforms is representative of the most common form of bedform association, at least as identified in the field. Unfortunately, the volume of data available on the nature of bedform associations is small. The reason for the relative absence of data on bedform associations may be the result of the absence of such features. It is also probable that the scope of some of the various papers was not intended as a discussion of associated bedforms.

In some respects the lack of data on bedform associations is a reflection of a weakness in the sedimentological literature for alluvial channels. Bedform association data may provide clues as to the reaction of bed material to varied flow, as a function of increased or decreased discharge, and thus serve to differentiate continuous flow and flashy flow channels. Furthermore, the identification of associated bed features in internal sedimentary structures may help to ascertain the preservation potential of bedforms under conditions of varied flow.

Paleocurrent Data. - The information supplied in the various papers on sedimentary features and paleocurrent analysis is of relatively poor quality, especially for paleohydraulic reconstruction. In most cases the authors have merely supplied general descriptions on the applicability of paleocurrent data, indicated vector resultants in the absence of a specified methodology, or data, or not utilized the technique. Is the paleocurrent information that has been illustrated useful to the reconstruction of general flow directions? The author is of the belief that the information does not convey, for the most part, reliable indications of flow direction. The main purpose of paleocurrent analysis is to provide details on flow directions in fluvial environments. The measurement of the dip direction of cross-strata, as an example, should provide an indication of the direction of lateral accretion; however, unless the true direction of flow can be ascertained from some more reliable reference, such as a valley or channel trend, the data obtained from the cross-strata will be of marginal value for the reconstruction of general flow directions.

In addition to the apparent inefficient usage of the paleocurrent data there is a lack of information on the utility or efficiency of paleocurrent indicators for modelling flow directions. Allen (1966) provided a ranking of paleocurrent indicators as based on their efficiency for modelling general flow directions. While the model is a valid attempt to classify and rank paleocurrent indexes, several assumptions are inherent in the hierarchical ranking that are not realistic. The first major assumption that is implicit in the model of Allen (1966), is that the major source of directional variance is from within individual samples. That is, the between-site variations in directions can largely be ignored. Saunderson (1976) demonstrated empirically that the between-site variance of paleocurrent data was significant for cross-bed directions in the Brampton esker.

The second major assumption that is implicit in Allen's (1966) model, is that all paleocurrent indicators can be ranked in terms of their efficiency for modelling flow direction. From the hierarchy proposed by Allen, the first and second order indicators are the channel form and point bars or other bar types, respectively. The highest order indicators are probably the best features for determining flow direction. The third and fourth order paleocurrent indicators are cross-strata and ripple marks respectively. In the absence of first and/or second order indicators it is doubtful whether the lowest order features can be used to accurately determine flow direction. The cross-strata and fourth order features are really only useful for modelling small-scale primary and secondary flow phenomena, and as a result, the measured directions are site-specific, and not reflections of average flow directions or trends.

Discussion of the Hydrologic, Hydraulic and Sedimentologic Data

Hydrologically and hydraulically it is possible to define the attributes of flow in alluvial channels. Furthermore, it is possible to distinguish between continuous flow systems and flashy channels on the basis of hydrological data. The data presented in this chapter is representative of the flashy channel type of flow. The most obvious feature exemplified by the hydrograph and the hydraulic measures is the wide extremes that occur between base flow and flood level discharge, and between minimum and maximum sediment transportation.

The sedimentological data that have been summarized in Table IV reveal several weaknesses in the existing literature. Sedimentary structures have been well documented for fluvial systems, although distinctive features cannot be used to differentiate continuous and flashy flows.

The problems associated with the sedimentology of flashy channels become most apparent when attention is focused on bedform associations and paleocurrent directions. Bedform associations may be difficult to identify in flashy channels because of the rapid changes in flow during an event, and the apparent low preservation potential of the bedforms and sedimentary structures. The lack of detailed studies on paleocurrent directions in flashy channels and alluvial channels in general, makes it impossible to assess the characteristics or trends of paleocurrent indicators.

The examination of sedimentation in flashy channels cannot be achieved without some difficulty. However, the synthesis of data derived from sedimentary structures and paleocurrent directions should reveal some of the peculiarities of flashy channels. The extraction of field data on the sedimentary structures and paleocurrent indicators from Highland Creek can be used as a case study for the formulation of a tentative sedimentological model for flashy channels. The author is emphasizing the term tentative, since the lack of substantive data, especially on paleocurrent directions makes it difficult to be more definitive with respect to sedimentological models for flashy channels.

CHAPTER THREE

SEDIMENTARY STRUCTURES

The previous chapter served to define the flashy characteristics of Highland Creek and to summarize the sedimentological data available on flashy alluvial channels. In the discussion of the hydrology and hydraulics of Highland Creek it was indicated that the most important phases of sediment transport occur during high magnitude flow events.

The data on sedimentary structures cannot be used to distinguish between flashy channels or continuous flow systems as exemplified by Table IV. The types of structures documented for flashy channels have been likewise published for continuous flow channels. The most apparent problems are to be realized in the assessment of bedform and sedimentary structure associations. It has been illustrated in Table IV that bedform associations have been documented in only a few studies. Typically, the associations are based on the study of features in continuous flow or in flashy channels that are characterized by sustained high flow stages.

The discussion of sedimentary structures provided in this chapter serves to describe the existing facies, facies assemblages, to discuss the hydrodynamic interpretations of the structures, and to examine the nature of bedform and facies associations.

Morphological Considerations of the Study Reach

The sinuosity of the study reach is 1.5. From the morphological definition of Leopold et al.(1964), the sinuosity of the study reach falls within the lower limits established for meandering channels; however, the channel is similar in appearance to some braided channels. The coarse texture of the material suggests that the dominant mode of sediment transport is by bedload. McGowen and Garner (1970) indicate that gravel-bed streams are generally bedload streams. The low sinuosity is interpreted as being the result of bedload transport.

Continuous flow channels are generally characterized by mixed sediment loads and a higher sinuosity (McGowen and Garner, 1970; Schumm, 1971).

The major morpho-structural features found in the study reach include point bars, and pool and riffle sequences. The study reach contains five bends, each of which is characterized by the aforementioned morpho-structural features.

Method of Analysis

Sedimentary Structures. - The internal structure of the point bars and their associated deposits were examined, since these features represented the most prominent sedimentary units. The evaluation of the internal structures was facilitated by digging small trenches into the formations. Generally, the trenches were located in proximal, mid-section, and distal locations, with respect to each macroform (point bars and riffle bars are considered to be macroforms in the terminology of Jackson, 1975b). Large-scale excavations could not be attempted without the use of mechanical equipment.

Grain Size. - The sampling procedure for grain size characteristics was oriented towards generalized sediment size distributions versus specific textural attributes of individual sedimentary structures. The individual distributions are based on bulk samples that were extracted from apparently homogeneous sedimentation units. The discussion of Jopling (1964b) provided clues as to the delimitation of sedimentation units. The units were defined by the internal sedimentary structures.

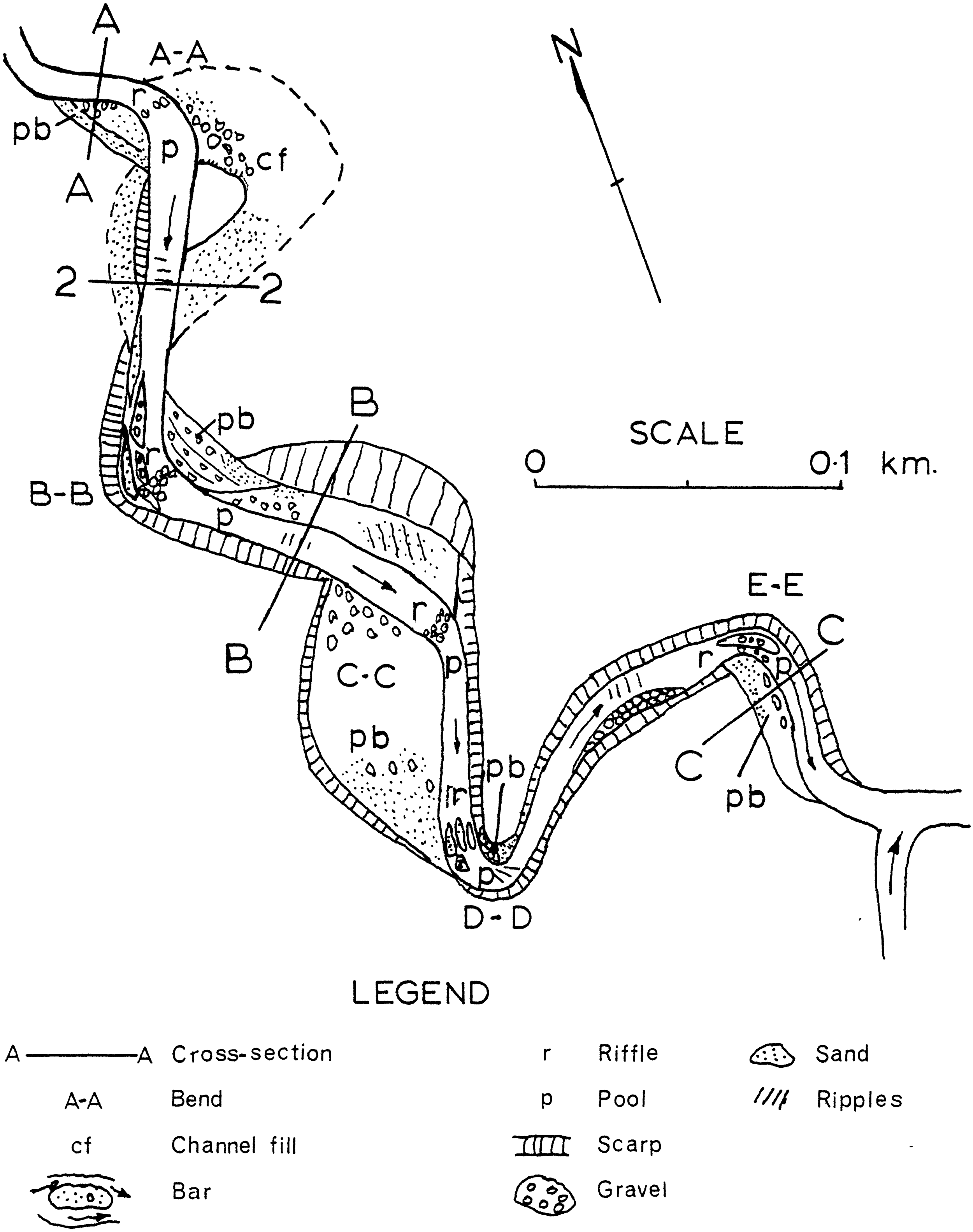
The bulk samples of each structural unit were extracted from the trenches by completely traversing the vertical faces with a mason's trowel.

At some locations the low profile of riffle bars and lower point bar platforms prevented trenching, since the water table was located within 0.1m of the water surface. In such cases, pits were dug to the water table and grab samples were obtained of the exposed material.

The locations of the individual samples for the facies analysis, and grain size distributions are indicated in Figures 3, 4, and 5.

FIGURE 3

SITE MAP OF THE STUDY REACH



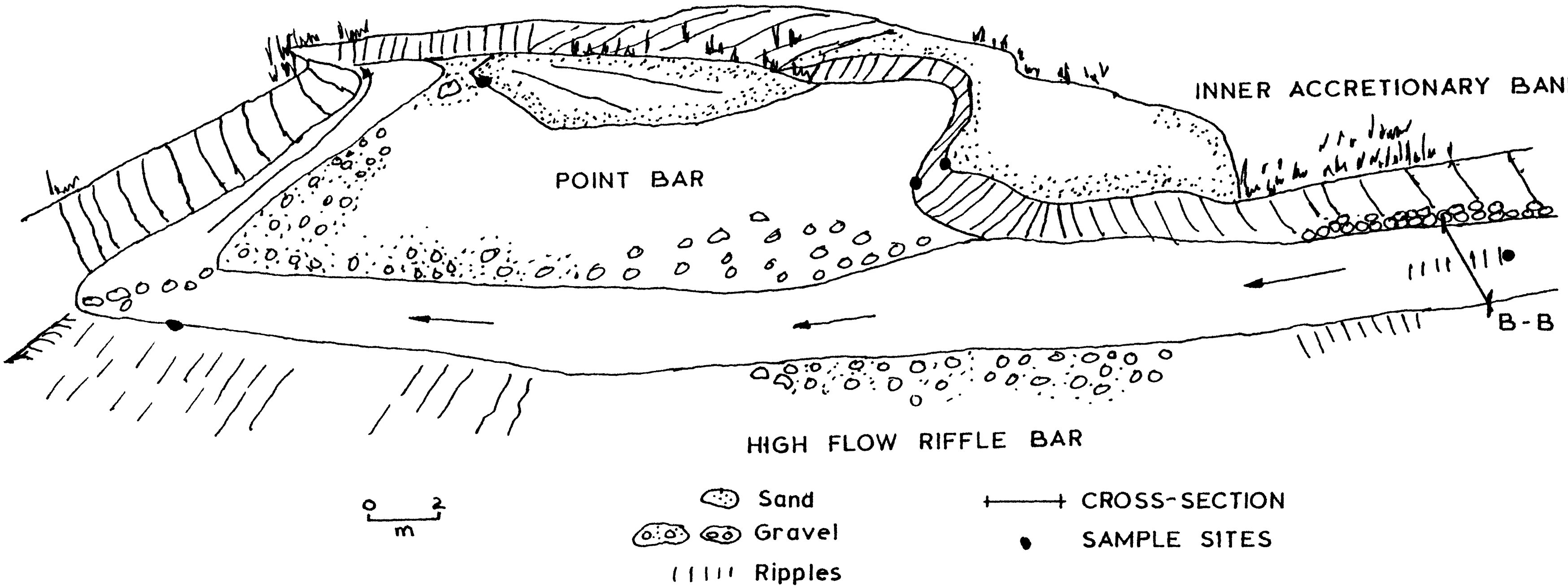


Figure 4. Line drawing of the point bar at C-C. The point bar is of a low profile, and is covered by a lag deposit of cobble gravel. The foreground is the high flow riffle bar. The flow is right to left. The scale of the diagram is accurate for the foreground, since the source of the sketch was an oblique photograph.

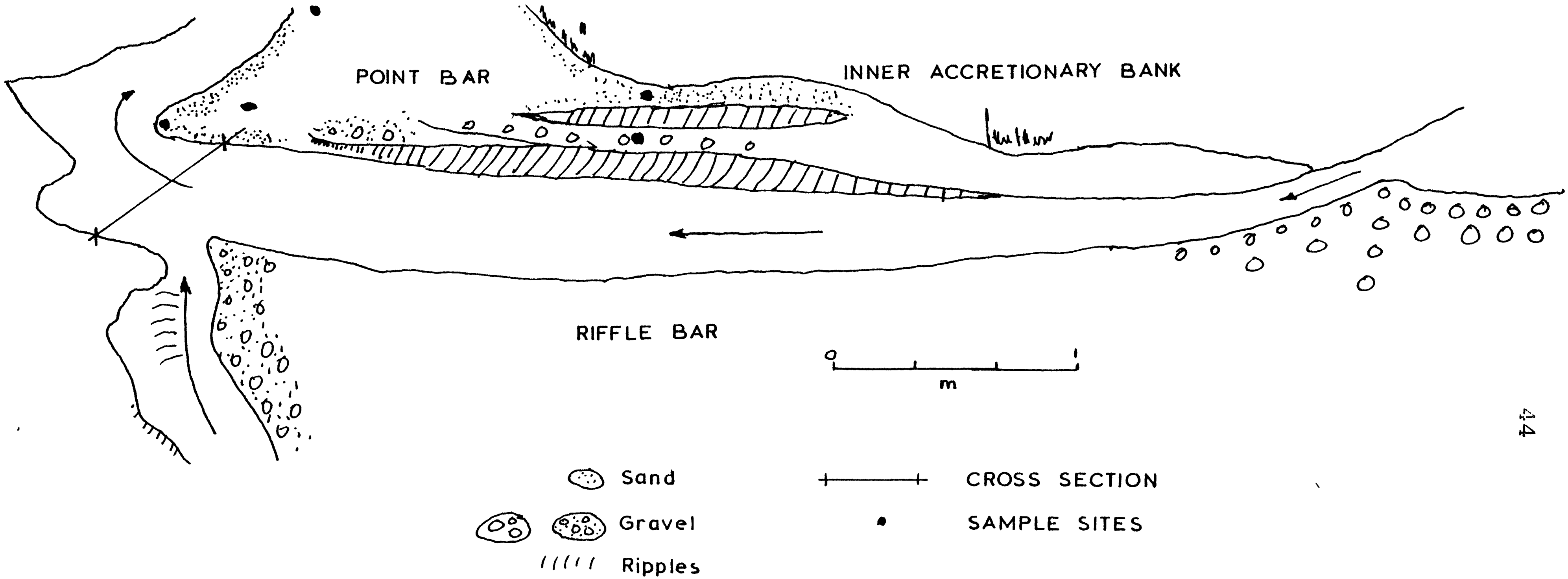


Figure 5. Line drawing of the bend at E-E. The original point bar was positioned in the middle of the sketch, prior to October 5, 1978. The occurrence of a high magnitude flow event on October 5, 1978, resulted in the downstream translation of the feature (a distance of 15m). The riffle bar acts as a braid-type bar at low flow, with the thalweg (main channel, in the middle of the diagram), and the smaller anabranch (foreground) being located around the bar periphery. Flow is from right to left. The scale is accurate for the foreground of the sketch.

Mechanical Analysis. - The grain size distributions of the samples were based on laboratory analysis. The bulk samples were easily subdivided into those containing gravel and those only containing sand or finer material. The fines of all samples were examined in the same manner. In all, 40 samples were analysed.

The total sample size of the gravel sand mixtures was sieved by hand, at half-phi intervals from -6.50Ø to -4.50Ø. The remaining gravel was removed by sieving at quarter-phi intervals, for 15 minutes on a Ro-tap mechanical shaker. The remaining fines were reduced to between 30gm and 70gm with a Humboldt riffle splitter, and then sieved for 15 minutes on the Ro-tap shaker. A multiplication factor was applied to the reduced weight of the fines in order to bring the sieved weights to the initial level. The samples not containing any gravel were simply split and sieved as above. The individual weights retained on each sieve were measured on a Mettler balance to 0.001gm.

The quarter-phi interval was chosen for the finer sediment in order to reduce the inaccuracy of interpolating between successive points on the sediment size distribution graphs.

The results of the sieving process were plotted as cumulative frequency distributions on arithmetic probability paper (Figures 6, 7, 8). The graphical methods of Folk (1974) were applied to summarize each distribution (see Appendix II for the summary statistics of each sample).

Facies Descriptions

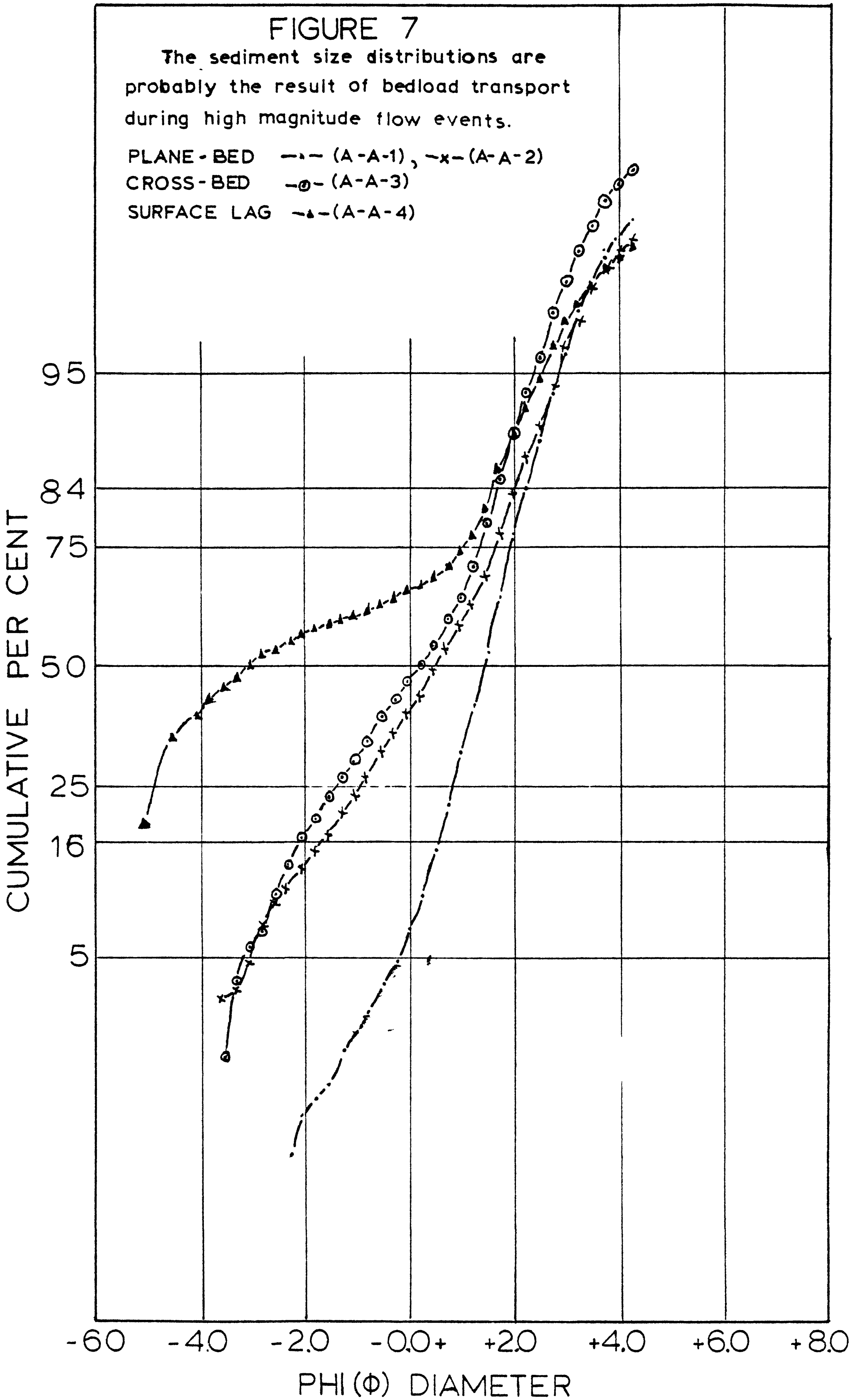
From a textural standpoint, the facies could be readily grouped into coarse and fine features. Rather than describe the interior of each point and riffle bar assemblage, and risk unnecessary repetition, the facies have been summarized in Table V.

Coarse Facies

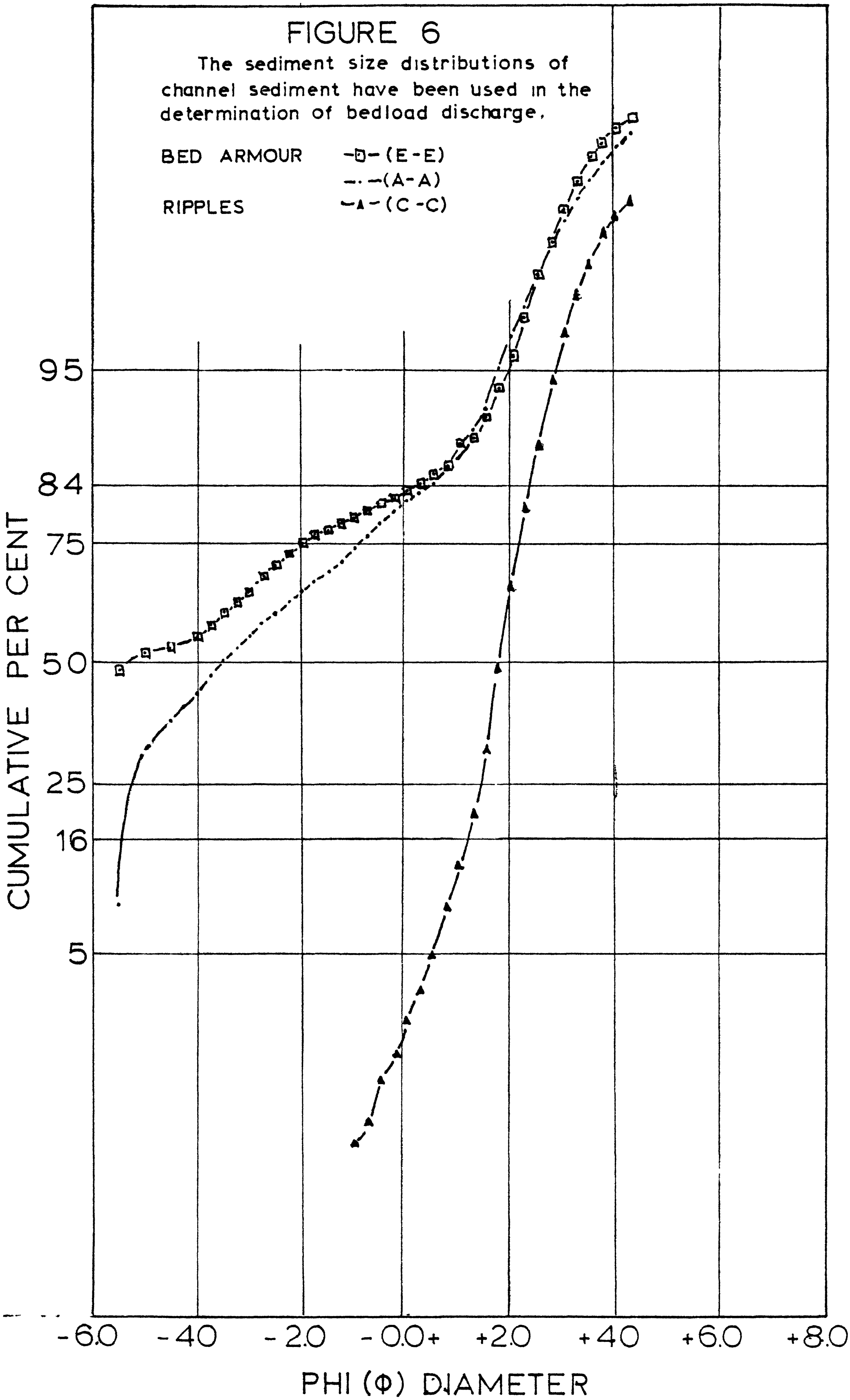
Plane-bedded Gravel. - This facies group includes the dominant sedimentary structure found at the study site, and elsewhere. The plane-bedded gravel is poorly defined as a result of the poor segregation of the sediment sizes during transport and deposition. In most cases this facies formed the lower part of the internal structure of the riffle bars, and the point bars (Figure 9).

Massive Gravel. - This facies was only found in the point bar at D-D, in the absence of other sedimentary

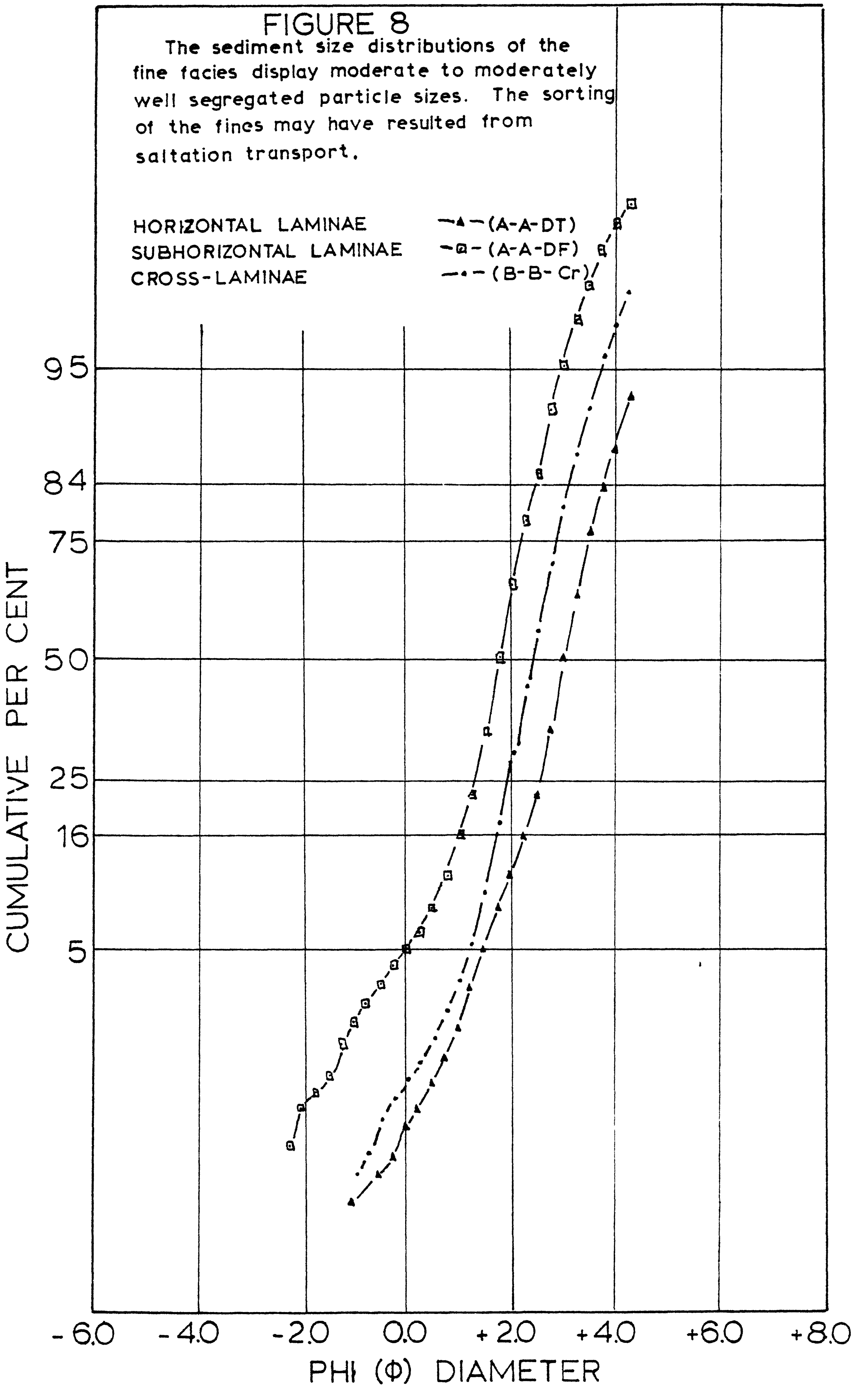
GRAIN SIZE DISTRIBUTIONS: COARSE FACIES



GRAIN SIZE DISTRIBUTIONS:
MID-CHANNEL, BED MATERIAL.



GRAIN SIZE DISTRIBUTIONS: FINE FACIES



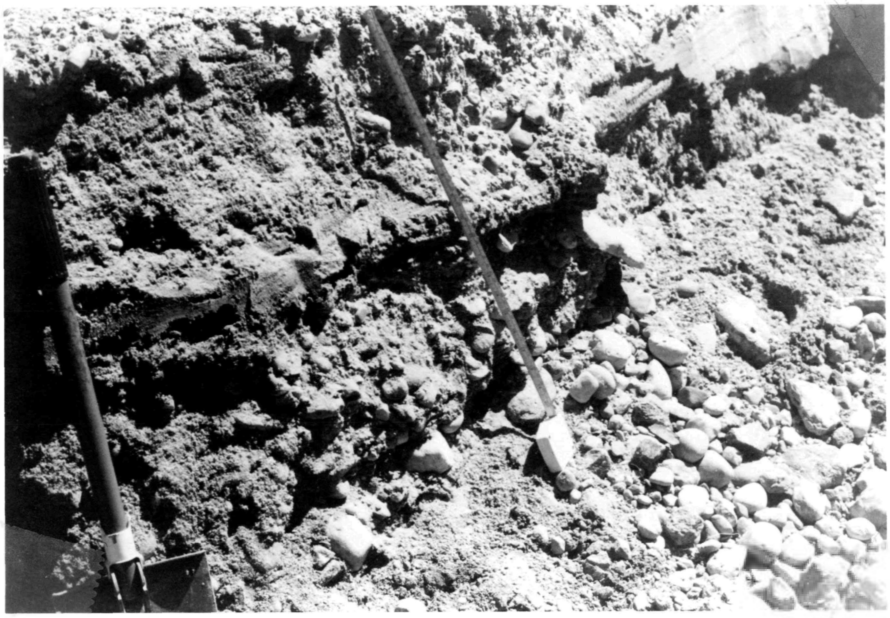


Figure 9. Coarse gravel facies in the point bar at B-B. The structure of the coarsest facies ranges from crudely stratified plane-bedding or cross-bedding, to massive. The example illustrated above forms poorly defined plane-bedded gravel.

TABLE V

Summary of Grain Size and Facies Data

Facies	Mean Size	Sorting
plane-bedded gravel	small to large pebble gravel -2.30ø to -4.40ø	very poor
cross-bedded gravel	small pebble gravel -2.32ø	very poor
open-work gravel	small to large pebbles -2.30ø to 4.40ø	poor
massive gravel	as for plane bedded gravel	very poor
interbedded sand and gravel	coarse sand to sandy pebble gravel +0.20 to -1.30	poor (unit in total)
horizontal lamination	very coarse sand to fine sand -0.45 to +2.65	poor to moderately well
subhorizontal lamination	fine to medium sand 1.55 to 2.90	poor to moderately well
cross-lamination	fine sand 2.40	moderately well
shallow cross-lamination	coarse sand 0.20	moderate

Textural data are based on the Graphical Methods of Folk (1974). The cumulative frequency graphs (Figures 6, 7, 8 as examples) form the basis of the statistical analysis of grain size distributions.

structures. The interior of D-D was formed of poorly sorted, massive gravel. It is probable that the massive gravel structure is representative of reworked sediment. Smith (1974) has indicated that the primary structure of channel bars can be obliterated by the reactivation of a bar surface, or by the modification of the interior via internal stresses. There was evidence to indicate that the bar surface was erosional. The presence of the erosional surface is indicative of the reactivation of the bar by recurring high flows. The author believes that the structure is due to the reworking of the sediment.

Cross-Bedded Gravel. - This facies is poorly defined cross-bedded gravel. The cross-bedded gravel facies was only found in the mid-section trench of the point bar at A-A. The poor bedding definition of the facies is the result of poor grain size segregation. The cross-beds dipped at 24° in the downcurrent direction, as seen in the one trench. It is suggested that the cross-beds form a lobate front although it is difficult to substantiate this statement without the aid of large-scale excavations.

Interbedded Gravel and Sand. - This facies was found in association with the plane-bedded gravel in the point bar deposits at A-A, and E-E, and in the riffle bar at C-C.

Typically, the facies occupies distal sections, in the upper stratigraphic levels. The definition of the bedding is good, with the alternating layers and lenses of sand and gravel being distinct.

Open-Work Gravels. - This facies consists of pebble to cobble sized clasts. In all cases, open-work gravel was found to either occur as a surface cover on the plane-bedded gravel, or as thin beds of material between units of massive or plane-bedded gravel. It has been inferred from the field evidence that the open-work gravel is a lag deposit formed during phases of bed armouring. None of the field examples were more than one bed (about 5.0cm) in thickness. The gravel texture is similar to that of the plane-bedded gravels, less the fine matrix.

Fine Facies

Cross-Laminae of Coarse Sand. - This facies constitutes shallow dipping (15^{o}) cross-laminae of medium sand to fine gravel. It was only found in the distal trenches of A-A. The formation is located distally of the coarse cross-bedded gravel.

Horizontal Lamination. - The plane or horizontal lamination dominated the fine facies, in terms of occurrence.

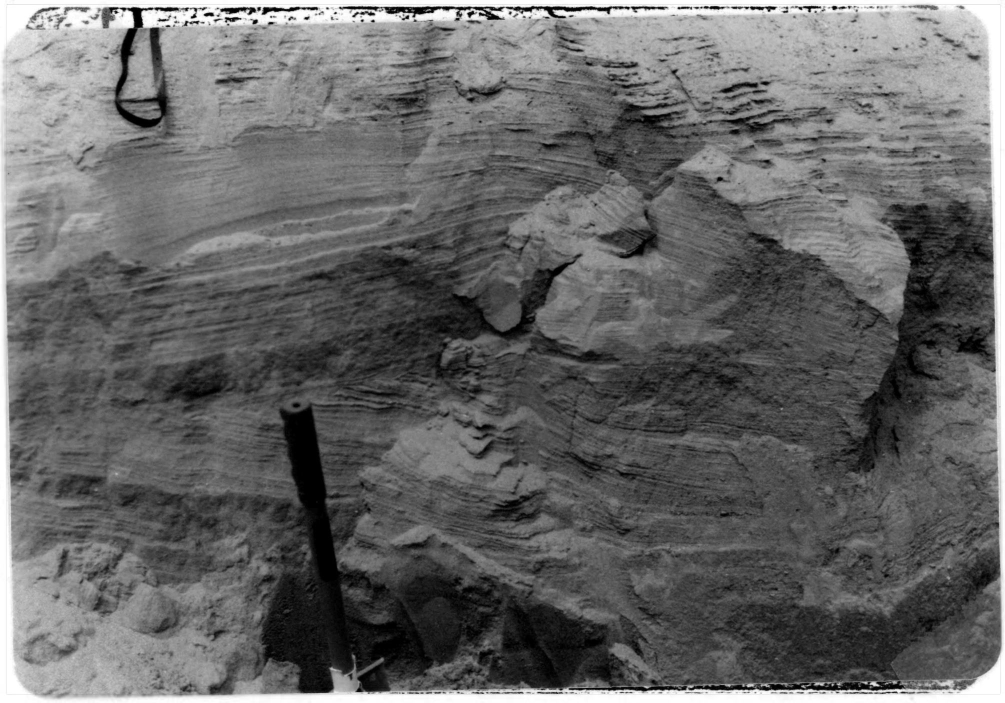


FIGURE 10. A channel fill sequence of plane/horizontally laminated fine sand. The top of the shovel handle points to an erosional surface. The facies were located in the chute deposits of the point bar at C-C.

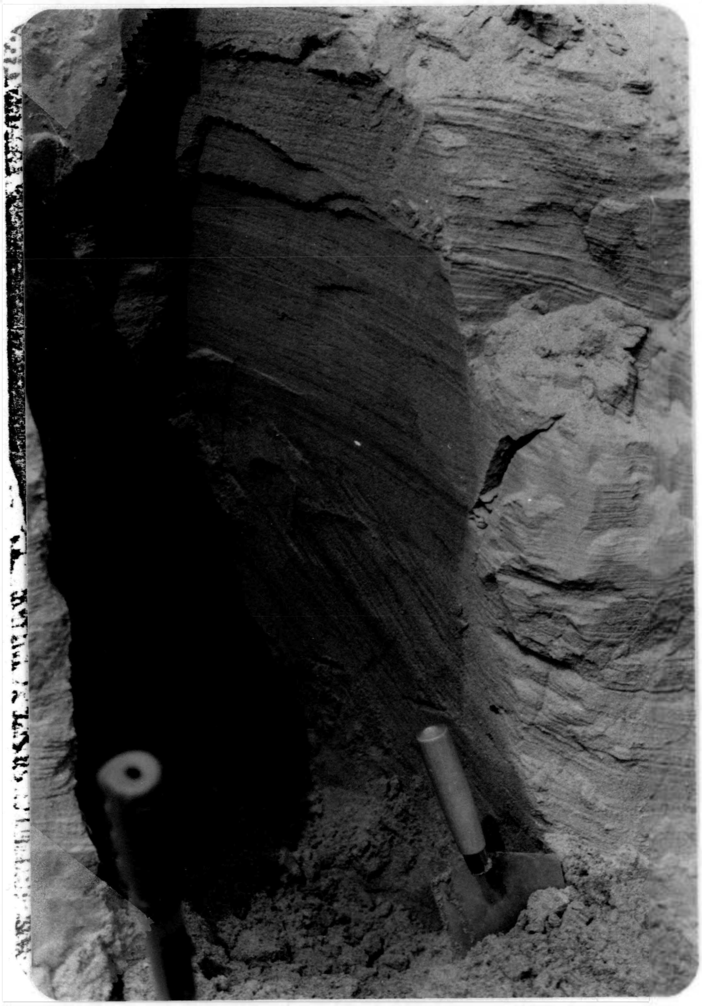


FIGURE 11. Plane/horizontal lamination and cross-lamination in fine sand. The photograph shows the trench that was dug into the face illustrated in Figure 10. The horizontal lamination changes to shallow dipping subhorizontal lamination in the distal direction. The section illustrated is located in the mid-section of the point bar deposits. The lower unit of cross-strata, was only found in the fine sediment of the point bar at C-C.

The material ranges from fine to medium sand. The definition of the laminae ranged from poor to good. The horizontal laminae occupied the uppermost structure in all of the cases examined. The inner accretionary bank deposits (Bluck, 1971) or chute deposits (McGowen and Garner, 1970) along the convex channel-side of each bend are the thickest units, in some cases attaining 1.0m. Thinner sequences of horizontal lamination were found to overlie the main point bar and high flow riffle bar surfaces, with the thickness increasing to about 0.3m, distally. Current ripples formed a surface veneer on the riffle bar surfaces. Other point bars and high flow riffle bars, on the West Branch, displayed current ripple veneers on the surfaces of the fine facies. Picard and High (1973) subdivided horizontal laminae into parallel and discontinuous strata, as based on the presence of parting lineation or streaming lineation. The present author was unable to conclusively distinguish between the two types in the field, and therefore, only one classification of horizontal lamination has been utilized (Figures 10, 11).

Subhorizontal Lamination. - This facies is comprised of laminae of fine to medium sand. The laminae formed convex-upward or relatively straight, dipping beds

(Figures 12, 13). All field examples were found along the margins of the point bar deposits, in the chutes or inner accretionary bank deposits.

Cross-Laminae of Fine Sand. - The only example of cross-laminated fine sand was found in the relict inner accretionary bank deposits of the point bar at C-C. The facies formed an apparent tabular set, and occupied a small channel fill formation. The foresets of the facies possessed a straight front, and a dip of 32^{o} (Figure 11).

Facies Assemblages

Point Bars. - The total assemblage of sediment at A-A measures 15m to 20m in length, about 10m wide and 0.4m high. The width of the point bar is approximately subdivided into thirds, with the lower bar platform, main point bar, and inner accretionary bank deposits comprising equal portions.

The proximal end of A-A is structurally dominated by plane-bedded gravel. The plane-bedded gravels are about 0.3m thick. The base of the sequence was not determined from the trench, so that the thickness estimate, above, is a minimum. The plane gravel sequence displayed individual bed thicknesses that ranged between

GURE 12. Subhorizontal lamination, convex-up profile. e section illustrated forms part of the chute fill posits in the point bar at A-A. The whole assemblage rms shallow dipping laminae, in the cross-section, th a convex-upward configuration. The definition of e individual strata is poor, probably as a result of the pid transport of the bed material.

The flow direction is inferred to have been toward e reader.

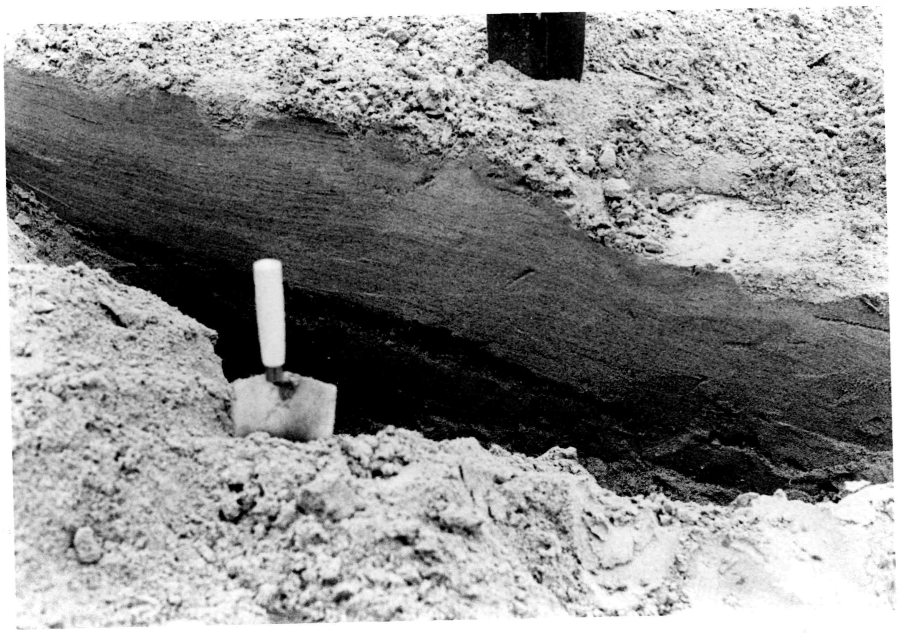


FIGURE 13. Subhorizontal lamination, irregular profile. The laminae were found along the periphery of the point bar at B-B. The strata form part of the inner accretionary bank deposit, and are superimposed on a substratum of irregular shape. The laminae dip towards the channel, perpendicular to the flow direction.

The flow direction is away from the reader.

about 2.0cm and 5.0cm. The plane-bedded gravel was covered by a 5.0cm thickness of open-work gravel. The surface of the gravel bedding was covered by a 1.0cm veneer of fine sand. Large pebbles and cobbles that were present in the gravel bedding, protruded through the surface of the sand. The proximal beds tend to dip slightly, less than 5.0^{o}, obliquely, in the upstream direction.

The mid-section trench of A-A displayed the general facies types as found in the proximal trench, although the lowest sedimentary unit was the poorly defined cross-bedded gravel. Because the trench was relatively shallow, the base of the cross-bedding could not be determined. The trench was 0.4m deep, and the cross-bedding was covered by a 0.1m thickness of plane-bedded gravel. The open-work gravel was also present on the surface of the plane-bedded gravel. Horizontal lamination covered the gravel bedding. The thickness of the plane-laminated sand measured 2.0cm on the channel side of the point bar. The thickness of the unit increased substantially, towards the convex channel bank.

On the channel side of the distal end of A-A, the structure is a combination of interbedded sand and gravel and shallow dipping cross-laminae of medium sand to fine gravel. The finer textured cross-laminated coarse sand occupies the lower stratigraphic position. The interbedded plane-beds of gravel and sand covered the cross-laminated coarse sand material. The interbedded gravel and sand facies is generally less than about 0.1m thick. The surface material consists of a 6.0cm thickness of horizontally laminated fine sand.

The inner accretionary bank deposits of A-A are composed entirely of horizontally and subhorizontally laminated sand (Figure 12). The thickest portion of the sediment is located near the convex bank of the channel, and measures 1.0m. Horizontal laminae were found to extend from the axis of the point bar to the convex bank as a surface cover. The subhorizontal laminae were found to occupy a chute located between the convex bank and the main point bar assemblage. Subhorizontal laminae were found to overlie the Pleistocene Scarborough Formation (Karrow, 1967). Coarser facies are entirely lacking from the sequence.

The point bar at D-D is difficult to assess structurally, since none of the previously described facies were found other than the massive gravel, and a thin veneer of horizontal laminae. The observations suggested a massive interior.

Perhaps plane-bedded gravels were present; however, the bedding definition was so poor, if it did exist at all, that the author has described the feature as being massive. From a textural perspective, the gravel material resembles that of the plane-bedded and cross-bedded gravel of A-A. The surface gravel was covered by a thin veneer of horizontal laminae, the thickness of which increased to about 4.0cm at the distal end.

Inner accretionary bank deposits were entirely absent from the assemblage at D-D.

The lower bar platforms of A-A and D-D are typically located on the channel side of the point bar assemblage. The lower bar platforms in both cases consisted of plane-bedded gravel. The surface of the platform is covered by a lag deposit of cobble gravel. In some cases the author noted the presence of a few imbricated prolate and discoid clasts.

The point bar assemblages, at B-B, C-C and E-E, were difficult to measure in terms of length and width, because in all cases the formations appeared to merge with the high-flow riffle sequences of the subsequent downstream bends. The problem, therefore, becomes one of establishing the boundaries between the two entities. In general the point bar/riffle length was less than about 100m. The plane-bedded gravel structure formed the bodies of all of the point bars, and the high flow riffles. The open-work gravels were present on most of the gravel surfaces.

Inner accretionary bank deposits of horizontal and subhorizontal laminae were found to cap the point bar sediments to a thickness of less than 0.3m, and they merge with the flood plain deposits of the convex bank. At B-B and E-E, subhorizontal laminae are separated by a 4.0cm thickness of fine to medium gravel (Figure 13). The boundary between the gravel layer and the lower unit of subhorizontal lamination is erosional. At E-E the surface cover of subhorizontal lamination has been eroded so that the sequence includes the lower unit of the facies, the gravel layer and a partially destroyed surface cover of fines.

The plane-bedded gravel forms a terraced bar cross-section in B-B. The terracing is presumed to be related to bed scour, and bend translation.

The point bar at C-C resembles the lower bar platform sediments found at other locations. Internally, the bar is composed of plane-bedded gravel. The surface of the formation is a gravel (cobble) lag deposit (Figure 14, 15).

FIGURE 14. Surface material of the point bar at C-C. The gravel material that can be seen in the photograph, protrudes through the surface veneer of fine sand. The sand may form part of the fine portion of coarse facies. The presence of the surface veneer and the armoured gravel bed suggests that the two structural components are related. Fine material that is winnowed from the pore spaces between the gravel clasts, may be transported over the bed surface. The accumulation of thin sequences of fines on the gravel bed may be indicative of the incomplete armouring of the bed surface prior to the abandonment of the surface.

FIGURE 15. The riffle bar surface at E-E. The photograph illustrates the armoured surface of the riffle bar at the proximal end of the feature. The gravel clasts consist of elongate/prolate cobbles and imbricated discoidal clasts, and larger occurrences of clasts that range from rhombohedral to spherical in shape. The flow is towards the reader.

The spaces between individual cobbles are filled with fine sediment. The fine sand veneer increases in thickness, distally, to a maximum of 0.1m. In the distal sections the sand forms horizontal lamination (Figures 16, 17).

The riffle surfaces at B-B, C-C, and D-D were covered by a thin veneer of horizontal lamination. The thickness of the plane-laminated sand unit increased to 0.3m, over a distance of 100m between B-B and C-C. The relatively thin surface cover of horizontal lamination may be a reflection of the rapid abandonment of the bar surface by the falling flow levels. Alternatively, the decreasing competency of flow during falling stage, may have resulted in ripple migration, during brief time intervals. The limitations imposed by restricted sediment supply, and low flow velocities may have precluded the accumulation of thicker sequences.

Riffles and Pools. - The author has included some data on the high-flow riffle sequences of B-B, C-C, D-D and E-E, in the previous section on point bar structures. The data has been included at that point because of the difficulty that was encountered in establishing the boundaries between point bar and riffle. The riffle sequences that are found at A-A and E-E differ somewhat from the other features since they do occur as separate forms. The low-flow riffle surfaces are never exposed, so that an internal

FIGURE 16. Distal end of the point bar at C-C. The lag surface of the point bar is covered by a 5.0 to 10cm thickness of horizontally laminated sand. It is suspected that the distal end of the point bar serves as a riffle bar for the bend at D-D, during high flow stages, since the transition zone between the two bends is relatively short. The entrance of the bend at D-D is at the right. The flow direction is towards the reader.

JRE 17. Horizontal lamination on the surface of the
nt bar at C-C - distal sections. The laminae that are
ıstrated in the photograph are representative of the
.ment facies shown in the lower left of Figure (16).
substratum of gravel is significantly finer than the
face lag of the proximal and middle sections of the point
. The material is coarse sand to fine gravel in size.
, is from right to left.

examination is impossible to achieve. Despite the difficulties, the author is suggesting that the structural evidence that has been extracted from the high-flow riffles and the point bars at B-B, C-C and E-E, is similar to that which is present in the riffle sequences in general.

The sedimentary units that are found in the pools of each of the bends are likewise submerged, at high and low flow, making observation impossible. Surface textures are the only valuable pieces of information that can be extracted. The pool at D-D, for instance, has a bed that is formed of medium to fine sand, the surface of which is covered by current ripples, at least at low flow, (Figure 18). The author might, therefore, speculate that the internal structure is that of plane-laminated sand.

The pool at A-A is a non-existent phenomenon at low flow. The sequence is filled in during the falling stage of high magnitude flow events. Leopold and Wolman (1960) have stated that during low flow, the pool is the locus of deposition, and at high flow stages it is the locus of erosion. The riffle sequences display the opposite trend.

FIGURE 18. Stationary current ripples in an anabranch at E-E. The ripples form during the last phases of sediment transport, probably during the falling flow stage of a high magnitude or moderate flow event. The internal structure of the features is horizontal lamination. The ripples form a surface veneer on the sand facies.

Interpretation of the Sedimentary Structures

The sedimentary structures or facies described above provide indications of the general hydraulic conditions that existed at the time of their formation. The subsequent discussion is intended to provide the author's interpretations of the sedimentary structures in terms of sediment transport theory.

The dominant facies found at the study site, in the point bars and the high-flow riffles was plane-bedded gravel. The poorly defined plane-bedded gravel constituted the lowest stratigraphic unit, or as in A-A, the proximal end and stoss side of the point bar. Based on this distinction, it is suggested that the plane-bedding is the first sedimentary unit formed. The poor definition of the beds, the coarse texture and the poor segregation of the sediment sizes indicate that the material was transported and deposited rapidly, probably as bedload.

The interpretations of grain size distributions by Visher (1969) suggest that material coarser than about 1.50ϕ in diameter will be transported as bedload in alluvial channels. The suggestion of the mode of sediment transport is based on Visher's method for dissecting grain size distributions. The size distributions are said to be comprised of bedload or traction, saltation and suspension populations.

By applying the concept of flow regimes of Simons and Richardson (1960, 1961), Harms and Fahnestock (1965) and Simons et al. (1965) to the interpretation of the plane-bedded gravel, it is suggested that the material was deposited during upper-flow regime conditions. The small percentage of fine clasts found in the plane-bedding may have been transported near the bed by saltation or as a graded suspension (Middleton, 1976). The inclusion of fines in the gravel bedding would have occurred during transport as such material becomes trapped in the pore spaces between the pebbles and cobbles. Moss (1972) suggested that the saltation population of a sediment size distribution may actually form a frame-work population over which the coarser bedload material is transported. Kellerhals (1967) confirms such an observation through experimentation on gravel transport. The incorporation of the fines is a result of the transport of gravel over the finer frame-work population. The preservation of the poorly defined structure would result from the rapid burial of the individual beds by overpassing sediment during aggradation.

It was stated above that the gravel was probably transported as bedload. Pebble and cobble motion would occur by rolling or sliding on the bed surface (Sundborg, 1956; Johansson, 1965, 1976). The initial deposit may have formed as transported bed material accumulated in front of or in the wake of an obstruction. The coarsest sediment may not have been in motion at such a time. Alternatively sediment may have accumulated at specific locations due to decreases in the instantaneous tractive stress and turbulence below critical transport thresholds (Smith, 1974).

The massive gravel structure as found in the point bar at D-D is somewhat anomalous, since no other examples were discovered at the study site. Miall (1977) indicated in his summary of braided river deposits that coarse, poorly sorted bedding may appear as massive or as crudely bedded formations. The processes responsible for the massive structure are not clear, although it is presumed that upper-flow regime conditions prevailed at the time of sedimentation. Smith (1974) stated, from field evidence, that during high magnitude flows, material may be scoured rapidly from the bed en masse, and rapidly dumped immediately downstream of the scour. The result may be a massive or apparently structureless feature. Alternatively, Smith (1974) indicated that the apparently massive interior of a channel bar may be of post-depositional origin. The initial structure may have resembled one of the aforementioned facies or any other combination of facies. The reworking of the primary structure could result from seepage forces as described by Simons and Richardson (1960, 1961) and Simons and Şentürk (1977), or from internal stresses that would accompany the repeated occurrence of high flow stage events.

Both of the interpretations are possible explanations for the massive structure, although the present author is of the belief that the structure of D-D is of post-depositional origin, as described by Smith (1974).

The poorly defined cross-bedded gravel, can only be found in the mid-section trench of the point bar at A-A. The cross-bedding is believed to be contemporaneous with the plane-bedded gravel facies in A-A. The progradation of the initial gravel plane-bed and the aggradation of the stoss-side of the unit should have resulted in the formation of a well defined slip-face or foreset front. The actual initial configuration of the deposit may have resembled a dune. Vertical accretion would have increased the height of the foreset front.

The poor definition of the individual beds is suggestive of continuous avalanching of gravel clasts down the foreset front. Under subcritical flow conditions the slippage of material is intermittent (Jopling, 1963, 1964a, 1965a, 1965b). The interval between each slip event is characterized by the deposition of suspended sediment that is dropped in the zone of flow separation. The occurrence of the two sediment populations results in the good definition of the beds. Under supercritical flow conditions, with sediment in continuous motion, the material would be continually added to the foreset crest, and slip events would be uninterrupted. The continuous avalanching of the gravel would prevent the development of the segregated sediment populations. Fine sediment that is carried over the crest of the foreset front may be removed, or if reverse flow exists in the zone of separated flow, the material may be incorporated into each bed as the fines are trapped in the pore spaces between the avalanching gravel clasts.

Jopling (1965a) provided experimental data on the characteristics of cross-bedding formed of various materials. For gravel bedding, Jopling determined that the foreset dip of the beds was about 35° under subcritical flow conditions. The cross-bedded gravels at the Morningside study site attained dip angles of 24^{o}.

With sand sized material the foreset front can be reduced in terms of dip angle, to a concave upward declivity by increasing the severity of the flow, and by decreasing the depth of the basin into which the sediment is diffused. Gravel foresets can retain a straight slope, angular bottomset contact, and relatively high dip-slopes under supercritical flow, because of the internal friction imposed on the structure by the grain-to-grain contacts. The poor bedding definition, coarse texture and low dip-slope angle is indicative of rapid transport and deposition.

The interbedded gravel and sand facies is interpreted as being the distal equivalent of the plane-bedded gravel. Its location in the upper levels of the stratigraphic sequence of A-A and elsewhere, indicates that the facies developed during the latter stages of gravel transport, and can probably be interpreted as being a transitional- to lower-flow regime structure (Simons and Richardson, 1961; Harms and Fahnestock,1965; Simons et al., 1965). The accumulations of sand do not appear to be continuous beds of sediment between the gravel units. Instead the fine material forms shallow lense-like structures that extend to about 1.0m in length. It is suggested here that the gravel material formed low profile dune features, with a maximum amplitude of 5.0cm. The low profile would have been controlled by the shallow depth of water over the point bar or riffle bar surfaces (Simons and Richardson, 1961). The dune configuration would develop as material is transported in discrete steps, rather than continuously as would be the case for upper-flow regime bedding. The combination of hydraulic factors would have allowed for the bed development. Flow would have separated from the crest of the lower-flow regime bed configuration, and a reverse circulation or vortex would have been established in the trough between successive dunes. Fine sediment that is transported in suspension or by saltation may become trapped in the zone of separated flow, and be subsequently deposited on the trough surface. Gravel transport must have been sufficiently rapid to bury the underlying strata and to preserve the initial primary structure. The absence of internal structures from within the individual gravel and sand beds makes it impossible to ascertain the presence of erosional surfaces.

The interbedded facies decreased in thickness distally. The reduction in thickness may be a reflection of decreased competency, or of a deficiency of available coarse material, during waning flows.

The author is of the belief that the open-work gravels are not of primary or depositional origin. The lack of a fine matrix is probably due to bed armouring processes.

The armouring of the bed results from the winnowing of the fine clasts after deposition. Bedload transport would have ceased (Kellerhals, 1967). Gessler (1967) and Kellerhals (1967) noted that the flow turbulence will penetrate the bed to remove the fines from the pore spaces between the larger clasts, if the flow conditions last for a substantial period of time. Simons and Richardson (1960, 1961) and Simons and Şentürk (1977) have indicated that the seepage forces may reduce the stability of a bed, provided fluid is being transferred from the bed to the flow. By interpretation, it is here suggested that the combination of seepage forces and flow turbulence act to liberate the finest clasts from the lower levels of the bed where the flow turbulence alone is of minimal proportions. Lane and Carlson (1954), Sundborg (1956) and Johansson (1965, 1976) have indicated that the formation of an imbricated bed could occur in some cases from similar processes.

The surfaces of the lower bar platforms, the point bar at C-C, and the low flow riffle bars are similarly armoured (see Figures 14, 15). The processes responsible for the bed configuration are the same as outlined above, although, the low profile features are related to intermediate flows. The coarse texture and the stable bedform may be an indication of a lack of, or a restriction of, bed-load transport during intermediate flows.

The fine textured facies are believed to have formed during the falling-flow stages, after the major portions of the coarse facies have formed.

Shallow dipping cross-laminae of coarse sand are found in the distal trench of the point bar at A-A, and are overlain by a thin unit of the interbedded gravel and sand facies. The author has interpreted the two as being contemporaneous with respect to flow stage and depositional phase. The low dip-slope (10° to 15°) was initially thought to be indicative of supercritical flow conditions. Picard and High (1973) have described a form of low angle cross-bedding that is analogous to the facies noted above. The feature records the deposition of plane-beds on sloping surfaces. From the interpretations of Picard and High it is suggested that the formation may be indicative of transitional- to upper-flow regime conditions, in the terminology of Simons and Richardson (1961).

The cross-laminated coarse sand records the down-current migration of the point bar at A-A, during conditions of low velocity, of waning flow. The textural qualities tend to substantiate the above statement. The downcurrent change from the coarse textured gravel cross-beds to the finer textured cross-laminated coarse sand indicates sedimentation under progressively decreasing energy levels. The absence of current ripples or ripple strata is indicative of relatively deep water, and flow conditions that approach the upper-flow regime (Picard and High, 1973) as noted above.

The interbedded gravel and sand facies would probably have formed during the same interval in which the shallow dipping cross-laminae were formed. The evidence for this statement is drawn from the fact that the interbedding covers the cross-strata. The coarse material would have been transported under lower-flow regime conditions, probably as small dune-like features, just before the supply of gravel sediment was cut off.

The horizontally-laminated fine sand is representative of lower-flow regime to transitional or lower-upper-flow regime configurations. Picard and High (1973) have identified two types of horizontal stratification in ephemeral stream deposits. The first type described by Picard and High (1973) is horizontal parallel stratification and the second is horizontal discontinuous stratification.

The first type of horizontal stratification is usually associated with the upper surfaces of a sand unit, while the horizontal discontinuous stratification is associated with thick sedimentation units in lower stratigraphic levels.

Picard and High (1973) have noted that the horizontal discontinuous strata are deposited in minor channel fill sequences or in channel bars under transitional-to upper-flow regime conditions. Sediment would be transported continuously along the bed surface in a traction carpet. During the peak of a high magnitude flow event, the fine sand may have been transported in suspension, and thus may not have been available for deposition in large quantities. After the gravel material was deposited and the severity of the flow conditions waned, the fines may have partially settled out of suspension to be transported as bedload or by saltation. The decrease in the severity of the flow would not have resulted in a corresponding change in the sedimentation pattern or the bed configuration due to a bed hysteresis effect. The presence of an armoured bed deposit between the plane-bedded gravel and the horizontal lamination demonstrates this fact. If the change from suspended to saltation or bedload transport had been instantaneous, then the lag surface would not have formed. The mode of sediment transport of a sediment mixture can be maintained over a range of hydraulic variables, and the bed configuration may be preserved over a range of Froude Numbers. The Froude Number values may in actual fact correspond to a different flow regime. That is, the formation of a specific bedform may lag behind the corresponding changes in the main hydraulic variables (Simons and Richardson, 1961). Such statements can further be illustrated by bedform stability fields (Simons et al., 1965) and depth-velocity-size relationships (Southard, 1971).

The persistance of transitional- to upper-flow regime bedforms may have allowed for the accumulation of relatively thick units of horizontally laminated sand over comparatively short time intervals. The favoured location for the deposition of the horizontal or plane-laminated fine sand is in the chute channels that are located between the main point bar deposits and the convex bank, of channel bends.

The bedding definition of the lower portions of the horizontal laminae is poor, due to the poor segregation of the sediment sizes, and is indicative of transport under upper-flow regime conditions.

During waning flows, the shallow depths and decreased flow competency may result in the evolution of lower-flow regime bedforms such as small-scale dunes or ripples. It is not necessary for the ripple of dune bedforms to result in the formation of cross-lamination, as demonstrated by Jopling (1964b). Therefore, the upper-flow regime plane-lamination may have gradually changed to a form of plane-lamination that is attributed to ripple or dune migration, and hence the lower-flow regime.

The upper horizons of the horizontal lamination illustrated in Figure 12 show increased bedding definition, as compared with the lower substratum. In some respects, the characteristics of the upper 5.0cm of sediment are analogous to the horizontal parallel stratification described by Picard and High (1973). The author has interpreted the surface layers as being representative of lower-flow regime conditions. The upper units of horizontal lamination are believed to be features formed by the migration of ripples and the presence of parting lineations. The presence of parting lineations can be used to estimate the abundance of the horizontal parallel stratification (Picard and High, 1973).

Picard and High (1973) have attributed the formation of the horizontal parallel laminae to low flow velocities under conditions whereby the current is strong enough to transport material as ripples and so weak that the finer suspension is deposited. Such an interpretation corresponds to the lower-flow regime conditions as defined by Simons and Richardson (1961), Harms and Fahnestock (1965), and Simons et al. (1965). Current ripples were found to exist as a surface veneer, in most cases.

The subhorizontal lamination described previously is similar to the inclined stratification described by McGowen and Garner (1970) and Picard and High (1973). The subhorizontal-laminae consist of singular sets of strata that cover irregular or erosional surfaces. In cross-section, the appearance is that of convex-upward laminae, or gently dipping laminae of irregular slope (Figures 12, 13), yet in the longitudinal section the appearance is that of the horizontal laminae. Characteristically, the laminae dip with the convex-up or irregular profile and terminate against the bottom or the opposite side of the depression. In all cases the subhorizontal lamination was found in chutes and along the margins of point bars. The dip of the laminae is usually transverse to the flow direction. In contrast to cross-bedding, the dip-slope is smaller and more directly influenced by the topography of the substratum (Picard and High, 1973).

The deposition of material does not occur by avalanching as is the case for cross-bedding; otherwise, the individual laminae would be inclined at a stable angle of repose. The deposition of sediment, forming the subhorizontal-lamination, is by currents moving along the dip-face, and the sediment is transported by traction. During the waning phases of flow, vertical and lateral accretion progressively build up the dip slope (Picard and High, 1973).

McGowen and Garner (1970) have stated that the inclined or subhorizontal strata are common in the point bar deposits of flashy channels, especially in the chute channels, located between the main point bar deposits and the convex bank.

The cross-laminated fine sands were only found in a channel fill in the inner accretionary bank deposits at C-C. The cross-strata formed an apparent tabular set in a small channel. The well defined cross-laminae indicate that the slippage of sediment down the foreset front was periodic (Jopling, 1963, 1964a, 1965a, 1965b), with the suspended material being deposited between the avalanche events. The foresets probably formed as a micro-delta prograded through the small channel during the latter stages of sand transport, in a waning phase of a high magnitude flow event.

Associations of Bedforms and Sedimentary Structures

Bedform associations in alluvial channels have been formulated from descriptive (Allen, 1968b, 1968c) and quasi-genetic and morphological data (Jackson, 1975b). In most cases, however, bedform associations have not been well documented in the sedimentological literature. Several studies have noted specific associations of bedforms, as illustrated in Table IV; however, few have explored the significance of such phenomena.

The models of associated bedforms as illustrated by Allen (1968b, 1968c), Collinson (1970), and Jackson (1975b) are largely based on the occurrence of continuous flows (Allen, 1968b, 1968c; Jackson, 1975b) or on the occurrence of sustained periods of high flow stages (Collinson, 1970). In meandering streams with continuous and competent flow, the sediment will be in continuous motion, and a variety of bedform types are expected to be in existence. If the process of bend migration occurs continuously, then it is further expected that the movement of sediment, and the burial of sedimentary structures will result in the preservation of associated bed features, as documented by Jackson (1975b).

Problems arise when the discussion is aimed at the identification of associated bedforms in flashy channels, especially if the texture of the bed material varies between coarse gravel and fine sand or finer material. The coarse texture of the sediment in Highland Creek, the extremes of flow conditions, and the rapidity with which hydraulic variables change during a dynamic event, essentially precludes the application of the bedform association models of Allen (1968b, 1968c) or Jackson (1975b), unless one considers the dynamics of the flashy channel hydraulics.

The data on bedform and sedimentary structure associations is lacking in the sedimentological literature, the reasons for which are not obvious. In the absence of such information, the present author has had to rely on the nature of bedform and sedimentary structure associations in Highland Creek, in an attempt to derive a model for flashy channels. The associations for Highland Creek have been identified, and summarized in Table VI.

TABLE VI

Associations of Bedforms and Sedimentary Structures

Bedform Associations	Superpositions	Sedimentary Structure	Preservation Potential
parting linaeation, current ripples, sand ribbons, (at low flow stage)	-parting lineation on ripples. -ripples on bed armour sand ribbons on bed armour.	horizontal lamination	low
bed armour	-bed armour and ripples on riffle and point bars	Open-work gravel	high
riffle bars point bars longitudinal bars transverse bars channel form	-transverse bars and longitudinal bars on riffle bars. -riffle bars, and point bars on channel form.	composites of small features	low for transverse and longitudinal bars. high for riffle and point bars

The above table serves to illustrate the nature of bedform and sedimentary structure associations. The small-scale bedforms appear during the latter phases of a high magnitude or moderate flow event. They are not preserved extensively. The large-scale macroforms persist in the channel, and possess high preservation potentials.

Discussion of Associated Bedforms and Sedimentary Structures in Highland Creek

The author subdivided the associations of features into those observed for the low flow stages, and for falling flow stages, as observed from the structural data. Because of the hydraulic variations between extremes, the subdivisions were deemed necessary. It is impossible to ignore the dynamics of flashy channels, especially Highland Creek, when attempting to derive and discuss the associations of primary sedimentary structures. One cannot list several features for flashy channels and suggest thay they are found to coexist all of the time. Only by selecting brief time intervals during a period of low or high flow can one identify groups of bed features. During the rising flow stage of an event, as an example, one can identify small-scale bedforms at the outset of sediment movement. As the energy levels of the flow increase to more severe levels, the initial features will be replaced by an entirely different group of bedforms (Smith, 1971).

In continuous flows, the bedforms that exist in the channel should be in equilibrium with the hydraulic variables. In a flashy channel, during a dynamic event, the changes in the hydraulic variables may occur so rapidly that bedforms never attain a balanced state, with respect to the flow conditions.

The author has not considered the types of bedform associations that might evolve during the rising-flow stage or peak-flow stage because such features cannot be observed from the sedimentary structures. The sedimentary structures observed at the site are the result of sedimentation under progressively decreasing energy levels. The replacement of bedform types under increasing energy levels, and the mass transport of sediment during peak stages essentially precludes the preservation of features attributed to the early phases of a dynamic event. All of the sedimentary features found in the Highland Creek channel are related to deposition during falling-flow stages.

Bedform Associations. - The author has identified the nature of some superimposed bedforms at the study site. The superimposition of bedforms can be subdivided into non-regime on regime bedforms as exemplified by parting lineations on ripples, regime on macroform, for example, ripples on riffle and point bars, and macroform on macroform, as illustrated by riffle and point bars on the channel form. The above classification of superimposed bedforms is based on the discussion of Jackson (1975b).

Observed Sedimentary Structures. - In some cases the presence of specific facies types in the channel deposits can be identified with certain bedform associations. The best examples of associated bedforms, as interpreted from the facies, are limited to the small-scale features as exemplified by the upper units of horizontal lamination and bed armour. The large-scale or macroform features are in all cases formed of groups or assemblages of sedimentary structures that may be associated with the lateral and vertical accretion of the smaller-scale bedform types. The macroform bed features, if they can be considered to be sedimentary structures, are superimposed on the channel form.

Preservation Potential.- The identification of bedform associations, as illustrated by Jackson (1975b), is dependent on the temporal and spatial continuity or variability of the flow conditions. In a continuous flow channel, bedforms may be readily preserved as sedimentary structures. The preservation potential of the bedforms is expected to be high because of the continuity of the hydraulic variables, and of sediment supply and movement. The occasional interruption of the average flow conditions by a flood may have little impact on previously buried bed features , unless the features are found in surface locations.

In a flashy channel, such as Highland Creek, sediment transport is restricted to the occurrence of a dynamic event. The amount of material transported and deposited may be high, and the interval over which sediment is transported and deposited may be relatively brief. During the course of a high magnitude flow event, small-scale, flow regime sensitive bedforms (ripples for example) may be eliminated and replaced by a new set of bedforms. Therefore, the preservation potential of the small-scale bedforms is low in flashy channels.

The large-scale bed features found in flashy and in continuous flows are relatively insensitive to the dynamics of the flow regime, and therefore, the preservation potential of the macroforms is high. Picard and High (1973) have implied that the sedimentary features that are stratigraphically significant, as for example point bar and riffle bar deposits, will persist. The features that are found on bed surfaces, or on bar surfaces are least likely to be preserved in ephemeral streams because of their exposure to subsequent floods. The lower strata found within the macroforms should persist from one event to the next.

The low preservation potential of the surface cover of horizontal lamination and parting lineation can be illustrated by the presence of erosion surfaces within units of the fine facies. The lowest parts of the horizontal lamination (horizontal-discontinuous lamination/strata of Picard and High, 1973) is not destroyed. Only the uppermost surface layers are subject to scour during subsequent high-flow stages.

The armoured bed feature has a high preservation potential, since the gravel facies (open-work gravel) has been identified in the riffle bar deposits and in the older alluvial material that forms the banks of the channel. The lag surfaces are representative of a stable gravel bed configuration.

Conclusions

The coarse facies probably formed by deposition from bedload material, with the inclusion of the fine clasts having resulted from the entrapment of fines in the pore spaces between the gravel clasts. Gravel transport and deposition are inferred to have been rapid. Such a conclusion is based on the poor definition of the bedding which in turn is the result of poor grain size segregation during transport. In some cases the surface of the gravel bedding was armoured. The armoured surfaces are indicative of an hysteresis between the deposition of the gravel and fine facies, despite the fact that the hydraulic conditions may have been conducive to the deposition of the fine sediment.

The surfaces of the low profile bar platforms and riffle bars are also armoured. The armouring of such surfaces may be attributed to intermediate flow levels, although generally speaking, the armouring processes would occur during the falling flow stages after the supply of fine materials has been cutoff. The fines found in the bed material are winnowed from the pore spaces of the gravel facies during falling-flow stage.

The fine facies are formed during the latter stages of a high magnitude event or during the falling-flow stage, as the conditions of the flow become less severe. Most of the fines were probably transported and deposited under transitional-to upper-flow regime conditions.

Current ripples were found as a veneer on the surfaces of the fine facies, on riffle and point bar surfaces, and in the low flow pool sequences. The ripple marks formed during the last phases of falling-flow stage. Their presence in the fine sediments are demonstrated by the upper layers of horizontal-lamination, and parting lineation.

The examination of bedform associations in Highland Creek has resulted in a distinction between the nature of bedform and sedimentary structure associations that are found in continuous and flashy flow channels. Bedforms in flashy channels are highly dependent on the variation of hydraulic parameters during high magnitude flow events. Only the largest-scale macroforms are insensitive to the short-duration dynamic characteristics of a high magnitude event.

The destruction and replacement of small-scale bedforms during a dynamic event results in a low preservation potential of such features. Only the most stable macroforms are preserved. The sedimentary structures observed in Highland Creek are indicative of deposition under progressively decreasing energy levels. Therefore, it is difficult to identify specific bedforms with flow conditions other than falling-flow stage. Bed lag and the rapid changes in the hydraulic variables during the course of an event may all but eliminate the possibility of identifying bedforms relating-.and peak-flow stages.

During rising-flow stage the bed material may be subjected to scour and mass transport. Furthermore, bedforms that may initially evolve in the gravel sediment may be replaced by a different set of bedforms, or obscured as the severity of the flow increases. The replacement or obscuring of bedforms during the rising- and peak-flow stage may make it extremely difficult to identify any bed features that might be associated with these phases of a flow event.

CHAPTER FOUR

PALEOCURRENT DIRECTIONS

Numerous studies exist in the sedimentological literature on the directional attributes of sedimentary structures and fabrics. The body of literature may be subdivided into methodology, application, and interpretation (see Potter and Pettijohn, 1963, for a detailed review and methodology, and Pettijohn, 1975, for a condensed review). Analytical and experimental studies of the directional properties of bedforms, specifically current ripples, have been completed by Allen (1966, 1968a). Field studies of cross-strata directions have been published by Bluck (1971), Dott (1973), Michelson and Dott (1973), Saunderson (1976) and others for several depositional environments.

Detailed accounts of fabric orientations and fabric mechanics have been provided by Lane and Carlson (1954), Sundborg (1956), Doeglas (1962), Johansson (1963, 1965, 1976), and Rust (1972, 1975).

Papers by Curray (1956) and Steinmetz (1962, 1964, 1975) provide discussions of the statistical methods as they relate to the processing of directional data. The method of Curray (1956) is based on two-dimensional data, while that of Steinmetz (1962, 1964, 1975) is based on three-dimensional data, in the form of spherical distributions. Steinmetz (1962, 1975) applied the statistical method of Watson (1956, 1966) and Watson and Irving (1957) for paleomagnetic orientations, to the study of cross-bed dip and direction.

Table IV illustrates that paleocurrent analysis has been neglected in studies of fluviatile environments. The directional information that is available has been published in the absence of statistical data, or has not considered the variability of directional indicators. Rust (1975) and Saunderson (1975, 1976) are representative of the few papers that have explored the significance of directional indicators, empirically and theoretically. The lack of analytical treatment on the variance of paleocurrent data severely restricts the utility of existing directional information.

Allen (1966) attempted to rank paleocurrent indicators on the basis of their efficiency for modelling general flow directions in rivers. While Allen's attempt appears to be valid, there is one limiting assumption inherent in the discussion that limits the value of the hierarchy. Allen (1966) has assumed that the source of variance in paleocurrent directions is from within-sites. The subsequent work by Saunderson (1976) illustrated that the between-site variance of cross-strata in eskerine sediments can be significant. Without the detailed assessment of paleocurrent variability, hierarchical models of paleo-current indicators become suspect.

Highland Creek is an active channel and presents an opportunity to examine, in detail, the relationship between paleocurrent data as derived from small-scale and large-scale fluvial landforms. In relict environments the lack of channel boundaries or valley trends makes it difficult to compare the paleocurrent directions obtained from small-scale bedforms and the larger-scale morphological features. The study of paleocurrents in a contemporary fluvial system can demonstrate the utility of directional indicators, and can be used for the formulation of paleocurrent hierarchies. Therefore, the purpose of the following discussion is to determine the nature and variance of paleocurrent indicators in Highland Creek, and to suggest a hierarchy of directional indicators.

Data Collection

Five cross-bedded units were measured for paleocurrent directions. The textural characteristics of the cross-strata varied from fine sand to pebble gravel. Because of the lack of abundant cross-strata all five units or samples were combined under one heading.

In all cases the cross-strata formed singular sets. Cosets of cross-bedding were not found at the site. Thus, the directional data are based on homogeneous cross-stratified units. In most cases, the small extent of the cross-bedding, and the coarse texture of the gravel facies prevented the extraction of large samples. Where possible, a minimum of 25 measures were taken. The sampling was performed by clearing a vertical face parallel with the dip direction of the bedding. A horizontal surface was cut through each unit to allow for the identification of the true dip direction of the individual beds. Each measurement was taken as being normal to a tangent that intersected the beds in the horizontal plane.

All samples were extracted from sections of 1.0m^3 or less. The small sample volume was selected to allow for a direct comparison of the individual sample vector resultants and a channel azimuth.

Current ripples occurred on subaerially exposed riffle bars, and point bars, and also in the active low-flow channel. The paleocurrent directions were determined by measuring the downcurrent orientation perpendicular to the ripple crest, at individual point locations. The bedforms included singular, narrow ripple-trains (less than 40cm wide, and 2.0m in length), and straight or sinuous crested ripples that extended to more than one-half of the channel width. Disturbed surfaces were not examined.

Measurements were obtained from a grouping of narrow, elongate depressions in the sand bed of the riffle bar at B-B, by simply recording the azimuth of the long axis. Only one group of such features were observed at the site. The depressions covered an area of 5.0m by 2.0m.

Fabric and pebble-cobble imbrication directions were derived from the surfaces of point bars and riffle bars. The fabric directions were obtained by measuring the orientation of the long axis of flat-lying, prolate cobbles. The author also extracted paleocurrent directions from the cobble clasts found within individual beds. The surface fabrics were obtained from areas that were about 5.0m^2 in extent. The internal fabrics were taken from bedding units that were up to 10cm thick. The lateral extent of the internal fabrics sample sites was 0.5m as a maximum.

The imbrication directions of discoidal cobbles were determined by measuring the dip direction of the A/B plane of individual clasts. The sample areas were restricted to about 5.0m^2.

The sample sizes of the fabric and imbricate groupings are the result of the author's attempt to maintain small sample areas. Sample sizes could have been increased by extending the area from which measures were taken; however, the author intended to utilize the azimuths of the channel at sample site locations as a comparison with the vector resultants of the fabric samples. The sinuosity of the channel necessitated the use of specific channel reference points.

Data Analysis: Summary Statistics

The data collected from the study site are two-dimensional distributions. Therefore, the method of

Curray (1956) was applied to each sample to determine the vector resultant and vector magnitude (Table VII). The method of Curray was selected because it is based on two-dimensional data, is not dependent on the selection of an origin, and can readily be applied to ungrouped data. The author has also included the standard deviation of each sample, and an accuracy index. The accuracy index is based on a simple function that is normally used to determine an optimal sample size. The optimal sample size is obtained from the combination of the standard deviation, a Z-score value of 1.96 ($\alpha = 0.05$), and a semi-angle of confidence (see Rao and Sengupta, 1970; Saunderson, 1975) in the form of

$$M = \left(\frac{sZ}{a}\right)^2 \qquad (2)$$

where M = optimal sample size
s = standard deviation of the sample
Z = Z-score at a specified confidence interval
a = semi-angle of confidence

Assuming that the paleocurrent directions are normally distributed for the sample sizes and sample areas chosen, the above function can be used to calculate the accuracy index for the individual samples. The value of a specifies the half-width of a confidence interval, given the assumption of normality.

TABLE VII

Paleocurrent Summary Statistics

Sample	mi	Tan θ	θ (Deg.)	Ri	L (%)	P	Ac (Deg.)	s (Deg.)
Cross-beds								
IAB-C-Cl	25	-2.2540	113.9	22.3676	89.5	$< 10^{-5}$	10.29	26.3
IAB-C-C2	10	-0.2533	165.8	9.8839	98.8	$< 10^{-4}$	5.50	8.9
DRS-C-C	06	-1.2850	127.9	5.6980	95.0	<0.01	14.50	18.1
A-A-MS	05	-1.4501	124.6	4.9144	98.3	<0.01	9.26	10.6
A-A-D	05	+8.6340	83.4	4.9750	99.5	<0.01	5.02	5.7
Composite	51	-0.0427	177.5	24.3790	47.8	$< 10^{-4}$	16.07	58.5
Ripple marks								
2-2	11	0.5140	207.2	9.2410	84.0	$< 10^{-3}$	19.15	32,4
C-C-RH	11	2.6395	069.2	8.3500	76.0	$< 10^{-2}$	23.46	39.7
D-D-P	17	0.8903	041.7	14.9300	87.8	$< 10^{-5}$	13.45	28.3
C-C-RI	09	0.3070	162.9	8.4600	94.0	$< 10^{-3}$	12.94	19.8
Composite	48	7.1660	097.9	16.1510	33.7	<0.01	18.89	66.0
Linear Depressions								
2-2	07	0.6870	214.5	6.6800	95.4	<0.01	12.89	17.4
Imbricates								
B-B-1	08	0.2460	013.8	7.3600	96.7	$< 10^{-3}$	10.19	14.7
B-B-2	08	0.1182	006.7	6.9400	86.7	<0.01	20.44	29.5
E-El	10	-1.3224	307.1	8.1836	81.8	$< 10^{-3}$	21.44	34.6
E-E2	07	-3.7789	284.8	6.2940	89.9	$< 10^{-3}$	19.04	25.7
Composite	33	-0.4748	334.6	23.1890	63.4	<0.01	16.72	49.0

TABLE VII (cont'd.)

<u>Fabrics</u>								
A-A-1	10	-0.0396	177.7	6.9360	69.4	<0.01	21.75	35.1
A-A-2	10	+0.5757	209.9	7.3034	73.0	<0.01	26.08	42.1
A-A-PB	22	-0.4317	156.6	17.0590	77.5	$< 10^{-5}$	16.05	38.4
B-B-R	10	-0.0585	176.6	7.5609	75.6	<0.01	17.32	27.9
B-B-R-2	09	-0.1966	168.9	5.5227	61.4	<0.03	28.93	44.3
C-C-S	08	-0.0121	179.3	4.2920	53.6	>0.05	36.80	53.1
Alt. bar E-E	21	+2.2870	066.4	15.6000	74.3	$< 10^{-4}$	17.88	41.8
A-A-Int	11	-0.5174	152.6	5.5932	32.7	>0.40	39.30	66.5
Composite	101	-0.4842	154.2	47.9175	47.4	$< 10^{-5}$	11.46	58.7
<u>Channel Direction</u>								
	12	-0.9172	137.5	8.7050	72.5	<0.02	24.05	42.5

---

mi = number of observations, Tan θ = tangent of the vector resultant, θ = azimuth of the vector resultant, Ri = vector magnitude, L = vector magnitude expressed as a per cent, P = significance of the distributions as derived from the Rayleigh Test, Ac = accuracy index of the samples (the value defines a half-width of a confidence interval for each sample, given the value of mi, Z at $\alpha = 0.05$, and the standard deviation s), s = standard deviation about the vector resultants, as defined by $s = \sqrt{2(1-r)}$, where the value of **r** is the vector magnitude expressed as a fraction of a unit circle (Mardia, 1972; Till, 1974).

Discussion of the Summary Statistics

The first column in Table VII is the sample size (mi). The samples are of unequal size because of the limited occurrence of each structural feature at each sample site.

The tangent of the vector resultant for each sample is obtained from

$$\tan\theta = \frac{\Sigma \sin\theta}{\Sigma \cos\theta} \qquad (3)$$

The azimuth of the vector resultant is a measure of central tendency. Vectors possess direction and magnitude, and therefore the azimuth value is the direction component.

The values of Ri and L indicate the magnitude of the vector resultants. Because the actual magnitude of paleo-current vectors is unknown, the common practice is to assume unit magnitude (Curray, 1956), unless some weighting factor is applied, for example particle size or shape. The vector magnitude (Ri) is derived from

$$Ri = \sqrt{(\Sigma \sin\theta)^2 + (\Sigma \cos\theta)^2} \qquad (4)$$

Typically the vector magnitude is expressed as a per cent of a unit circle, and is derived from

$$L = \frac{Ri}{m} \cdot 100 \qquad (5)$$

where

m = the number of observations in each sample.

Curray (1956) applied the Rayleigh Test to test the significance of the two-dimensional orientation distributions against circular uniformity or randomness. Curray has provided a table and a graph of values, based on the magnitude of each vector resultant and the number of observations. The graphical method is the simplest and most convenient way of determining the significance of the directional data, since it is not based or dependent on constant sample sizes.

From the application of the Rayleigh Test, it can be demonstrated that all but two of the paleocurrent samples are significantly different from randomness. The determination of a significance level is somewhat arbitrary. The present author has selected the 0.05 level of significance. That is, no distribution is accepted as being significantly different from circular uniformity unless there are less than five chances in 100 of its being due to pure chance (Curray, 1956).

The individual samples and the composites of each sample grouping were plotted as circular histograms on Lambert azimuthal equal-area graphs (Figures 19, 20, 21, 22). The vector resultants have been plotted on a map of the study site (Figure 23).

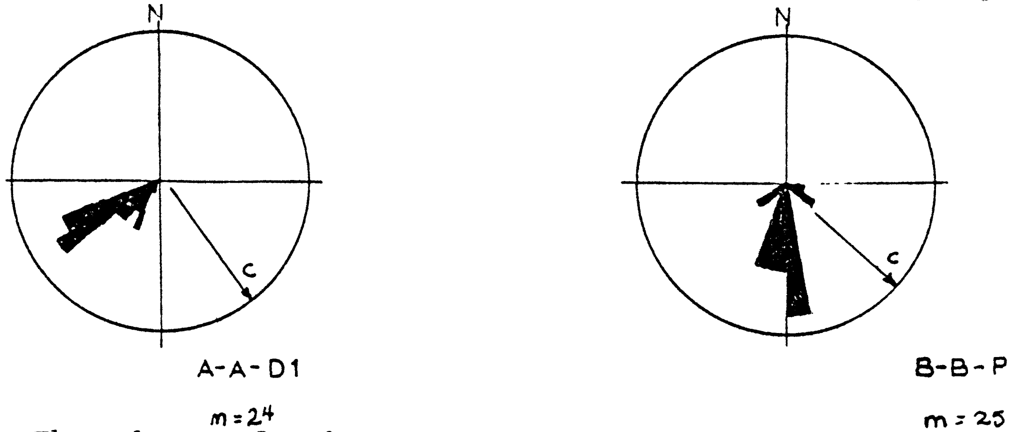
The graphical plots of the orientation data can be used to visually assess the strength and variability of the paleocurrent indicators. Typically, the cross-bed directions are clustered about the vector resultant. The standard deviation of the individual samples is relatively low as shown in Table VII.

The ripple mark directions are relatively clustered, although the spread of data about the vector resultants is greater than for the cross-beds.

The fabric graphs illustrate high variations or deviations of the individual clast orientation about the vector resultants. Sundborg (1956) and Johansson (1965, 1976) state that the distribution of clast orientations may be bimodal or polymodal with dominant parallel- and transverse-to-flow modes. Oblique orientations are also to be expected. The parallel-to-flow orientation is the most stable position, and the result of elongate clasts having been transported by hopping or saltation, and from the pivoting of clasts once the downcurrent motion has ceased. The transverse orientations are the result of elongate clasts

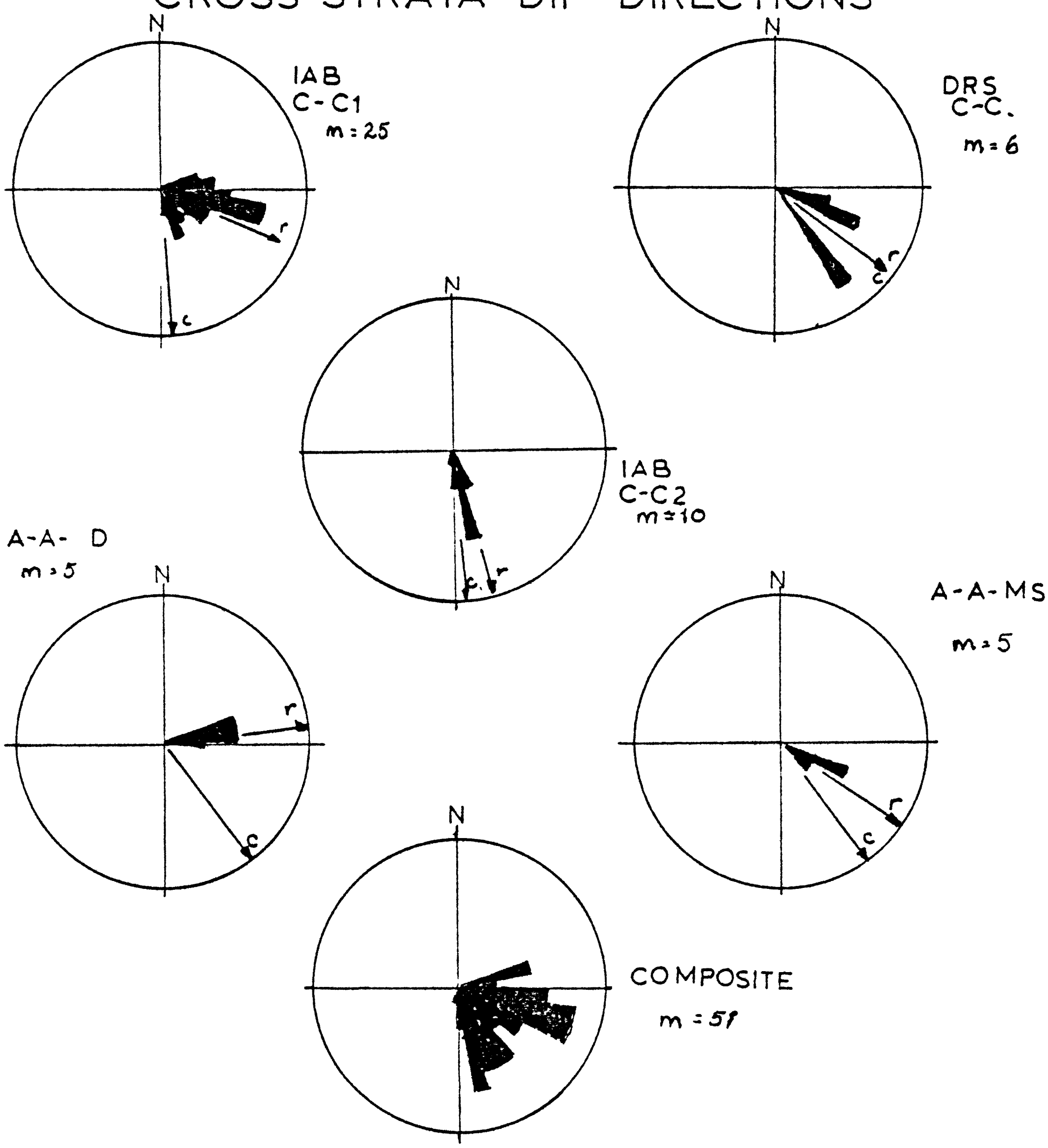
FIGURE 19

SUBHORIZONTAL LAMINATION DIRECTIONS



The plots of subhorizontal laminae directions were determined from the dip directions of the strata.

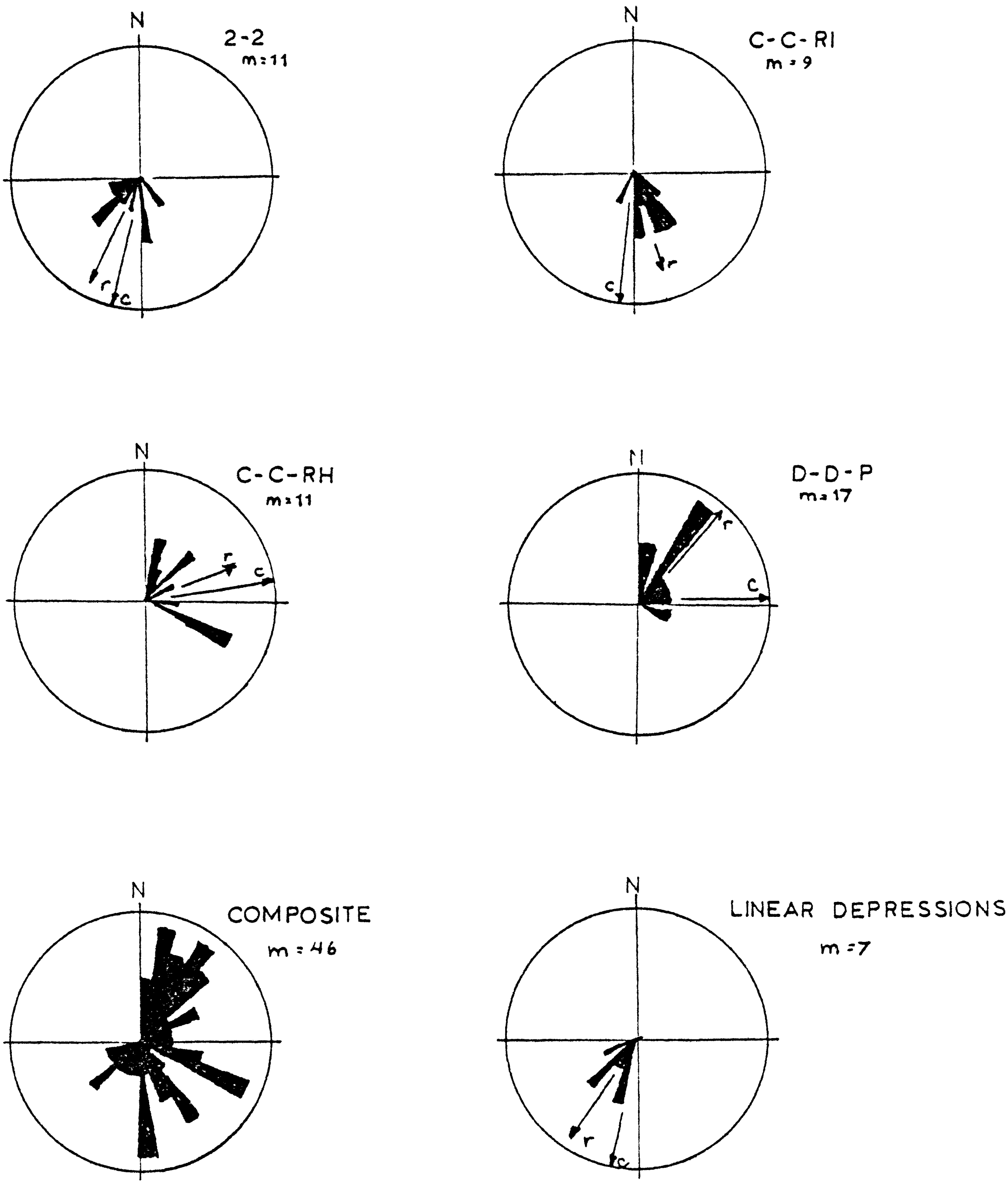
CROSS-STRATA DIP DIRECTIONS



The plots of the cross-strata directions have been based on the dip directions of the bedding. c - channel orientation, r - vector resultant of the sample

FIGURE 20

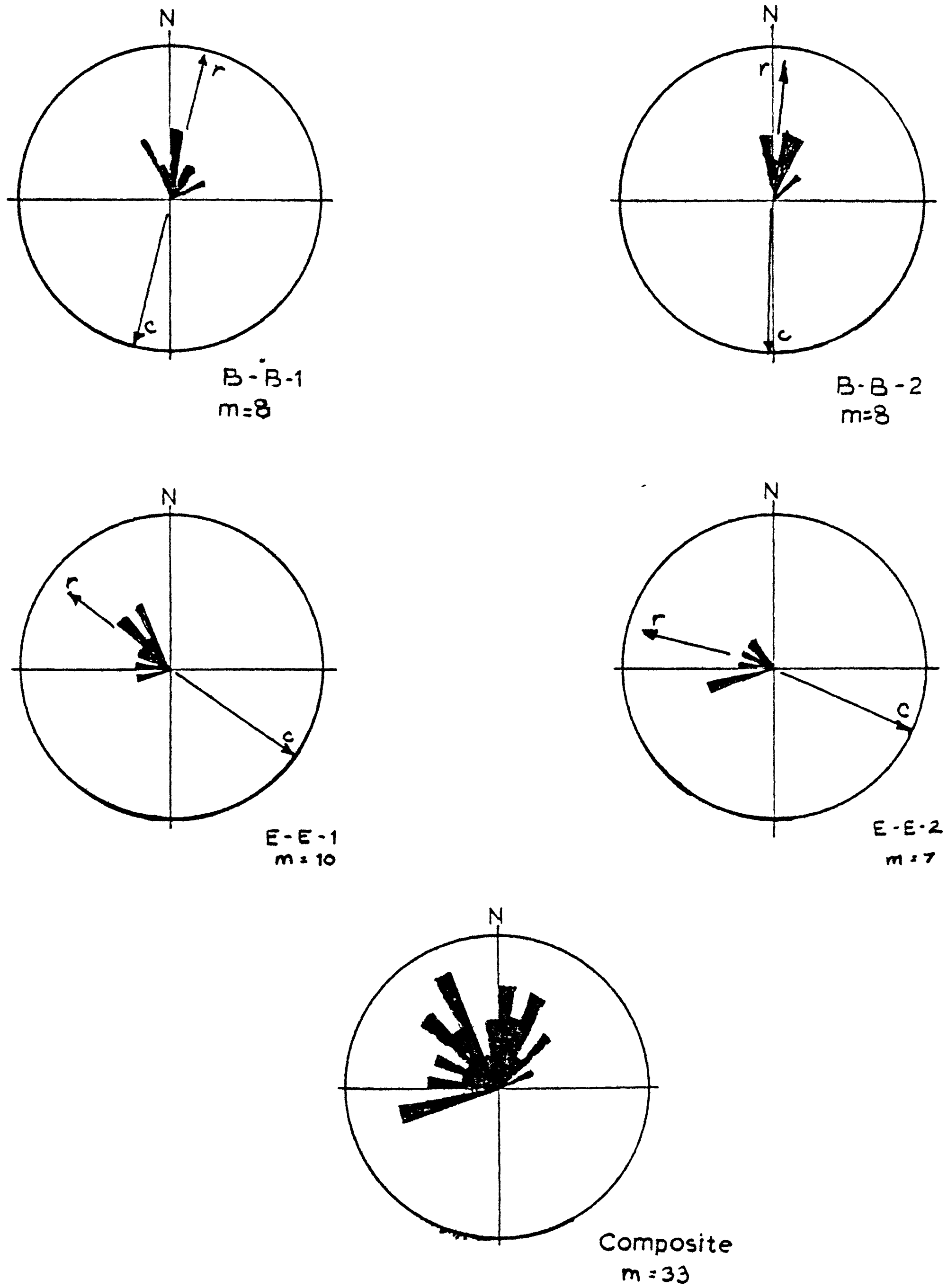
RIPPLE MARKS & LINEAR DEPRESSION ORIENTATIONS



The orientation of ripple marks was derived from the measurment of a line, normal to the tangent that intersects the ripple crest. The plot of the orientation of linear depressions is based on the measurement of the long axes of the bed features. c - channel orientation, r - vector resultant of the sample

FIGURE 21

IMBRICATE ORIENTATIONS

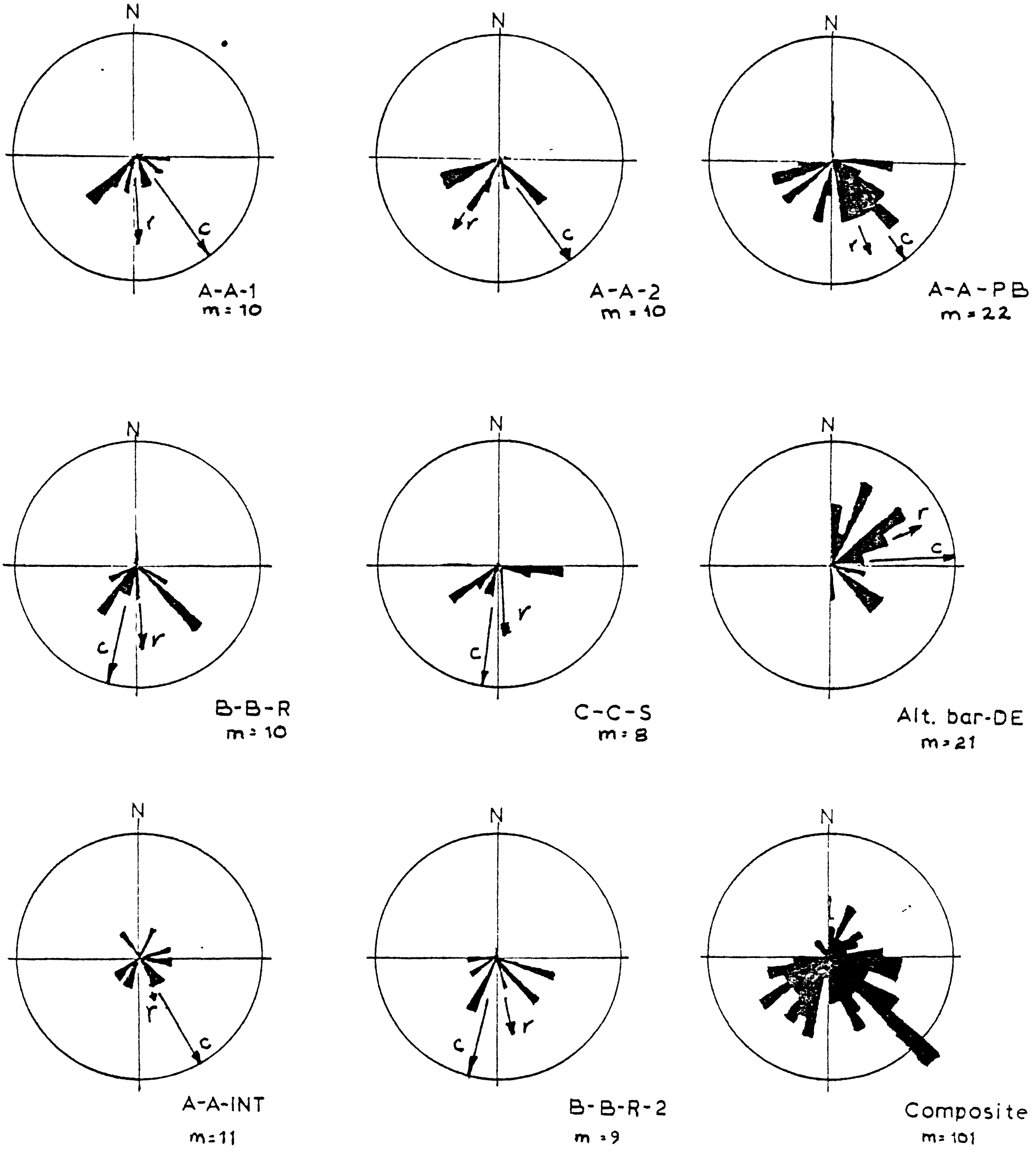


The plots of the imbricate orientations are based on the measurement of the dip direction of the A/B plane of discoidal cobble clasts. The preferred orientations are approximately 180° to the true flow direction.

c- channel orientation, r - vector resultant of the sample

FABRIC ORIENTATIONS

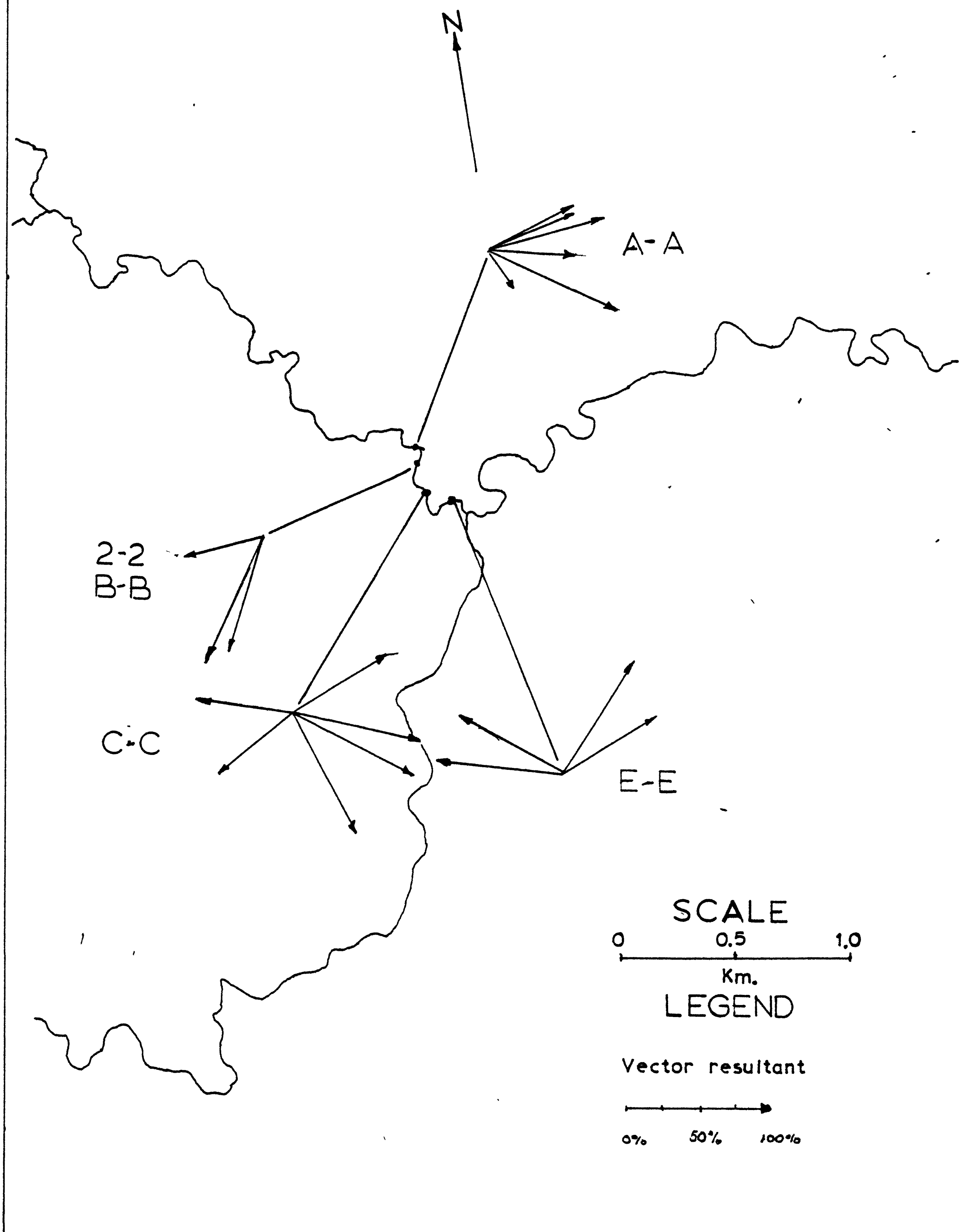
FIGURE 22



The fabric plots shown above are based on 180° distributions. The samples are plotted as deviations from the downcurrent flow trend, assuming the data ranges between $\pm$ 90° of the parallel-to-flow direction.

c - channel orientation, r - vector resultant of the sample

HIGHLAND CREEK: PALEOCURRENTS



having been rolled along the bed surface. The transverse orientation is the least stable form. Oblique orientations result from the partial rotation of clasts, or from bed obstructions that prevent the complete pivoting of clasts from the transverse- to parallel-to-flow orientation.

Imbricated clasts are typically oriented parallel-to-flow (A/B plane). The parallel-to-flow orientation is the most stable and most common imbrication form, and in general the imbricate directions deviate very little from this trend. It should be realized that the dip of the A/B plane of imbricated discs is 180° to the flow direction.

Analysis-of-Variance of Paleocurrent Indicators

Potter and Pettijohn (1963) have recommended the use of analysis-of-variance methods for the development of an efficient paleocurrent sampling procedure. In the present study, the restricted occurrence of paleocurrent indicators precluded the development of an efficient sampling plan. However, the available data can be examined by analysis-of-variance to ascertain the source of directional variation and to establish the relative efficiency of the indicators for modelling flow directions.

Watson (1966) and Rao and Sengupta (1970) have stressed that the conventional statistical methods are inappropriate in the analysis of circularly distributed data. Although azimuths can be established from the angular data by selecting an arbitrary origin, conventional methods for determining the arithmetic mean do not provide an accurate measure of central tendency. Similarly, Watson (1966) argued that the methods of analysis-of-variance, from conventional statistical methods, cannot be indiscriminately applied to the circular distributions.

Rao and Sengupta (1970) have adapted the three-dimensional analysis-of-variance methods of Watson (1966) and Watson and Irving (1957) to the two-dimensional orientation data. Therefore, the method of Rao and Sengupta is applicable to the data as extracted from Highland Creek.

The easiest approach to the analysis-of-variance is to maintain a constant sample size, as noted previously. Since the samples are of variable size, a representative or weighted sample size had to be calculated for each group of data (from Rao and Sengupta, 1970) from

$$m = \frac{1}{n-1}\left(N - \frac{\Sigma mi^2}{N}\right) \qquad (6)$$

where

n = total number of sample sites.
N = total number of observations.
mi = individual sample sizes.

The analysis-of-variance was applied to each sample group, for example cross-beds, ripple marks, and so on.

The significance or heterogeneity of variance was determined by the comparison of a calculated F-score with the critical values of the F-distribution at (n-1) and (N-n) degrees of freedom (Johnson, 1973). The value of F is calculated from

$$F = \frac{(\Sigma Ri - R)}{(N - \Sigma Ri)} \cdot \frac{(N-n)}{(n-1)} \qquad (7)$$

where

Ri = magnitude of the vector resultants for each sample.
R = magnitude of the grand vector resultant for each sample grouping

If the value of the calculated F is not significant, then the between-site variation of paleocurrent directions can be ignored, since the source of variance is derived from within-sites (Rao and Sengupta, 1970). The results of the F-test and the analysis-of-variance are summarized in Tables VIII and IX. In all cases the calculated F value exceeded the critical values defined by the F-distribution.

TABLE VIII

Calculations for Analysis-of-Variance

1 Source of Variation	2 df	3 SS	4 MS	5 EMS
Between sites (B)	n-1	$R_i - R$	$(R_i - R)/(n-1)$	$\frac{1}{2}(\frac{1}{n} + \frac{m}{B})$
Within sites (W)	N-n	$N - R_i$	$(N - R_i)/(N - n)$	$\frac{1}{2W}$

Table VIII indicates the source of computations for analysis-of-variance test (After Rao and Sengupta, 1970).

(the numbers across the top of the table indicate the column)

TABLE IX

Analysis of Variance Results

	F(cal)	F(0.05)	B	W	K	r	l
Cross-beds	85.3411	2.45-2.37	1.569	0.137	2.987	64.977	1.96
Ripples	119.7370	2.84-2.76	0.720	7.239	2.860	66.404	1.96
Imbricates	123.6800	2.92-2.84	4.776	3.434	16.330	27.900	1.96
Fabrics	10.5480	2.17-2.09	2.429	1.850	17.589	26.766	1.96
Subhorizontal laminae	85.8130	4.08-4.00	2.636	9.179	5.211	49.194	1.96

B = between-site precision estimate
W = within-site precision estimate
K = concentration estimate about grand vector resultant
r = semi-angle of confidence
l = Z-score (α = 0.05)

Tabulated F-score values are from Johnson (1973).

Results of The Analysis-of-Variance

The results of the analysis-of-variance indicate that the between-site estimate (B) of the population variance is significant for all of the paleocurrent indicators at $F_{0.05}$.

Based on the discussion of Rao and Sengupta (1970), the values of the between-site (B) and within-site (W) population variances can be derived by equating column four (mean sum of squares) and column five (expected mean sum of squares) from Table VIII.

The results (Table IX) indicate that the low precision of B and W for the paleocurrent indicators may be the result of highly variable flow directions during the formative stages of each sedimentary feature. The highest precision of the between-site population variance is found with the data on the fabric and imbricate orientations.

The precision estimate K provides an indication of the concentration of the paleocurrent populations around the grand vector resultants for each sample group. The higher the value of K, the greater the clustering of directions about the grand resultant. The value of K can be obtained by substituting the appropriate variables for each sample grouping, into the expression

$$K = \frac{1}{(mnW)^{-1} + (nB)^{-1}} \qquad (8)$$

the rearrangement of the relation yields

$$n = K\left(\frac{1}{B} + \frac{1}{mW}\right) \qquad (9)$$

and

$$m = \frac{1}{W}\left(\frac{n}{K} - \frac{1}{B}\right) \qquad (10)$$

The expression for n indicates that as m approaches positive infinity, the value of n approaches K/B. The relations are important because the minimum number of sample sites can be determined from them (Rao and Sengupta, 1970 ; Saunderson, 1976). Saunderson (1976) provided an example to illustrate the effect of the above relation, but rather than reiterate his analysis, the present author will apply the argument to the Highland Creek data. In the example, the precision estimate K for the study site, for imbricated discs, is 16.33. A minimum of four locations is necessary to obtain K = 16.33, in estimating the grand vector resultant for the study site. The measurement of only a few more imbricates is necessary to attain K = 16.33 if additional samples are obtained in the future. As Saunderson (1976) has noted, as the number of sites, n, increases the number of required observations, m, decreases for each site.

One of the more important variables is the semi-angle of confidence about the grand vector resultants. The semi-angle of confidence is defined by

$$K = l^2/r^2 \qquad (11)$$

where

l = Z-score probability = 1.96, for $\alpha = 0.05$.
r = semi-angle of confidence in radians.

From the data on the imbricates, the semi-angle of confidence is 27.9°, with K = 16.33, and $Z_{0.05} = 1.96$.

For the cross-beds and the ripple marks, as listed in Table IX, the precision estimates K for the whole study site are low and the corresponding semi-angle of confidence levels are high. The semi-angle of confidence for all of the sample groups, including the fabrics and imbricates can be reduced by increasing the value of K (Rao and Sengupta, 1970; Saunderson, 1976). That is, if r = 0.174 radians (10°), at $\alpha = 0.05$, then K = 127. As noted above, the value of K can be obtained from various combinations of n and m. Particular attention must be paid to the significance of B with respect to W, since the greatest efficiency associated with the various combinations of n and m depend on the precision of B and W, and their respective significance levels (Saunderson, 1976). From the discussion of Rao and Sengupta (1970) and Saunderson (1976), it is apparent that the increase of n would be more desirable, with respect to the cross-bed, imbricate, and fabric data than an increase in m, because the precision of B exceeds that of W in all three cases. Conversely, the precision of W exceeds that of B for the ripple data, thereby making an increase in m more efficient than an increase in n. However, the precision estimates of both B and W for all paleocurrent indicators are so low that increases in n and m are desirable.

Importance of Analysis-of-Variance

The precision estimates of the between-site (B) population variance are statistically significant at $F_{0.05}$, for the cross-bed, ripple, imbricate and fabric data. The low precision of B indicates that the reliance on one sample would be insufficient for determining the precision estimate K about the grand vector resultants, for each sample grouping. The low precision of W indicates that the within-site variability of the directional data is high also.

The important factor to be examined is B, since it is apparent that an inaccurate estimate of K would result from the examination of one sample site, especially if B is significant in all cases, and therefore, more than one site is necessary for the analysis of flow directions. The trends displayed by B and W, for the cross-beds, imbricates, and fabrics are similar to those displayed by the data of Steinmetz (1964) and Saunderson (1976), for cross-strata. The ripples in Highland Creek display the reverse trend. The analysis-of-variance results of the ripple data indicate that the within-site variance is lower than the between-site variance.

The precision estimates of B and W for the fabrics and the imbricates are the highest for all of the samples taken. Likewise, the value of K indicates the relatively high precision of the fabrics and the imbricates, about the grand resultants. Studies by Lane and Carlson (1954), Sundborg (1956), Doeglas (1962), Johansson (1963, 1965, 1976), and Rust (1972, 1975) indicate that the A/B plane orientation of imbricates deviates very little from the parallel-to-flow trend. The precision of K for the fabrics is difficult to assess, since elongate clasts typically form bimodal or polymodal distributions (Sundborg, 1956; Johansson, 1965, 1976).

Interpretations of Paleocurrent Data

From the graphic illustrations of Figures 19 , 20 , 21 , and 22 , it can be shown that the orientation properties of the imbricated discs closely approximate the general flow or channel directions at the respective locations. The imbricated clasts constitute the best paleocurrent indicator at the study site, because the individual vactors only deviate by about $\pm 10^{\circ}$ from the respective channel trends. The slight deviations in the orientations may have resulted from the development of secondary flow components. The generation of the secondary flow components could result from the deflection of flow around obstacles on the bed, or more likely, from the turbulent structure of the flow.

Other variations in the orientation of imbricates can probably be attributed to the nature of the clast support structure. In this case the fines are removed from the interstices between the pebble and cobble clasts, so that the imbricates come into contact with the underlying substratum of material. The points of support for the individual clasts may be off-center, thus resulting in an oblique-to-flow orientation. If the author had simply recorded the azimuth of the a-axis trend for each clast, the deviations may have been significantly reduced. However, the A/B plane was the focal point of attention, since it is the most outstanding directional feature of discoidal clasts. Major deviations from the parallel-to-flow orientation are not to be expected with imbricates, as the pattern is the most stable orientation fabric of elongate and discoidal clasts (Lane and Carlson, 1954; Sundborg, 1956; Johansson, 1963, 1965, 1976).

It is apparent from the cross-bed directions, that primary and secondary flow directions vary from site to site. Within-site variations are small, with vector resultants displaying high magnitudes, and overall distributions that are charcterized by moderate standard deviations. The peculiarity of the variations of the orientation of the individual beds would be more apparent, for example, if cross-bed directions were examined around the periphery of the point bar at A-A. Such deviations from the main flow direction are indicative of the localized variations in the flow trajectories over the bar surface. It is suggested that the cross-beds form a lobate front, thereby resulting in the variable paleocurrent directions. The pattern of the flow, as determined by the channel geometry, sample site locations and so on will account for the differing foreset orientations. The flow pattern as illustrated by Smith (1974), in channel bends, and associated with the formation of point bars, demonstrate the variations in the downcurrent and transverse flow components and the effect produced with respect to foreset progradation. The initial point bar deposit might have resulted from the reduction of the instantaneous tractive forces and flow turbulence below critical sediment transport levels (Smith, 1974). Once the bed configuration becomes established, it is expected that the formation will aid in the modification of the turbulent flow structure, as stated by Smith (1974). Thus, the turbulent nature of the flow pattern may be the most important factor contributing to the variable orientation of the individual foreset beds.

The ripple marks tend to be oriented obliquely to the general flow direction. The analysis-of-variance results provided very low precision estimates, both for the between-site and within-site populations, and for the whole site. The reasons for the statistical anomaly are not clear, although it is suspected that the analysis-of-variance results were affected by the calculation of the grand vector resultant. Azimuthal deviations of 180° between the specific site locations may have produced the very large standard deviation about the grand resultant. The azimuthal variations between the ripple orientations and the channel directions, at each site, are about 20° on average.

The ripple orientations are highly affected by the localized flow conditions, especially tractive forces, which in turn are affected by the turbulent structure of the flow (Simons and Richardson, 1960, 1961; Simons et al., 1965). Allen (1966) has stated that the directions of ripple marks are responses to the micro-scale characteristics of the flow adjacent to the bed surface, and therefore, they will not reflect the true pattern of the flow in general.

Fabric orientations do not display any specific trends even though the vector magnitudes are of moderate value. It is suspected that the fabric orientations as displayed by the vector resultants could be altered by varying the sample sizes or by using 360° distributions. The typical fabrics studied by Johansson (1965, 1976) possessed strong transverse- and parallel-to-flow orientations. The Highland Creek samples are small, because of the author's attempt to restrict the sample areas.

The works of Sundborg (1956) and Johansson (1963, 1965, 1976) indicate that the clast orientations reflect the mode of transport, although in many cases post-depositional processess may be responsible for surface fabrics. Elongate cobbles that are transported by rolling or sliding tend to be oriented transverse-to-flow, while hopping or overturning motions should result in a parallel-to-flow trend (Sundborg, 1956; Johansson, 1976). Prolate cobbles that are initially oriented transverse-to-flow may attain a parallel-to-flow orientation, once forward motion has stopped, by pivoting about the center of gravity. The presence of an obstruction on the bed may act to impede the rotation of a cobble, with the result being an oblique-to-flow orientation. Rod or blade shaped cobbles may maintain a transverse-to-flow orientation once forward motion has stopped.

The primary fabric of a bed can be modified by bed armouring, as demonstrated by Gessler (1967) and Kellerhals (1967). If the bed material supporting the pebble or cobble clasts are smaller than the gravel sizes, and if the flow turbulence during falling-flow stage is capable of penetrating the pore spaces between the larger clasts, then the fines will be removed. Such a process will alter the support structure of the substratum and thereby effect a change in the fabric, as implied by Lane and Carlson (1954) and Johansson (1965, 1976). The armouring process should effectively increase the stability of the bed.

Hierarchies of Paleocurrent Indicators

The ranking of paleocurrent indicators can be based on two different groups of data. Allen (1966) grouped all paleocurrent indicators into four different orders, for one hierarchy, as a function of the efficiency of the indicators for modelling the flow directions in an alluvial channel. As noted previously, Allen (1966) assumed, implicitly, that the source of paleocurrent variance is from within-sites and that all paleocurrent indicators could be ranked in one hierarchy.

The statistical data on the paleocurrent directions, for Highland Creek, demonstrate that the between-site population variance is significant for all of the paleocurrent indicators. The question is whether or not these small-scale directional indicators efficiently provide general flow direction information. In relict environments, morphological features such as the channel form or the valley may not be preserved intact; therefore, without the large-scale morphological references for determining paleoflow directions, the value of the small-scale sedimentological paleocurrent indicators may be subject to debate. The presence of channel scours on the Pleistocene bed surfaces, in the Highland Creek bank materials, may be indicative of former channel boundaries; however, the boundaries of such paleochannels do not extend upwards into the overlying alluvium. At many other locations, channel scour features are absent, although the presence of alluvium is indicative of previous fluvial activity in the Highland Creek drainage basin. Therefore, the absence of morphological information could prevent the accurate determination of paleocurrent directions, from small-scale bedforms and/or sedimentary structures. The problem may be particularly acute for flashy channels, since the poor preservation potential of most sedimentary structures may eliminate the occurrence of potentially useful paleocurrent information. This problem cannot be resolved by the present author because of the lack of additional paleocurrent information on flashy channels in the literature.

The study of paleocurrent directions in contemporary alluvial channels, and the assessment of hierarchical rankings of paleocurrent indicators may prove to be useful to the study of relict fluvial environments. The rankings presented in the subsequent discussion are based on statistical data, and on vector resultant data from a contemporary alluvial channel.

Statistical Ranking of Paleocurrent Data

By simply relying on the directional data obtained from the cross-bedding, the ripple marks, the imbricates and the fabrics, it is possible to rank these indicators on the basis of the precision estimates K, about the means of the respective grand vector resultants. In fossil fluvial sediments the evidence of past fluvial processes may be solely based on the preservation of small-scale sedimentary structures. From the data on the paleocurrent indicators of Highland Creek, it is illustrated that the best paleocurrent indicators are elongate cobble clasts.

since the highest concentration level (K) about the grand vector resultants is associated with the orientation properties of the fabrics, as determined by the a-axis orientation of the prolate cobbles. However, the polymodal or even the bimodal nature of the distributions of the fabrics may make the actual interpretation of flow directions difficult, in the absence of more reliable information. In some cases, the vector resultants were normal to the actual flow direction due to the strong transverse components in the measured samples. The presence of lag surfaces in the stratigraphic sequences, and the association between the orientation of prolate cobbles and imbricates may increase the utility of the fabric data.

The second best indicator of paleocurrent directions would appear to be that of the imbricated cobble discs. The actual orientation of the A/B plane (dip direction) is 180° to the true flow direction. By coupling the paleocurrent data on the imbricates with the expected high preservation potential, as inferred from the structural data, imbricates may be the best paleocurrent indicators available for gravel bedded, and possibly flashy, streams. The low standard deviation of the samples and the low deviation from the channel trend suggests that imbricates are the best indicators.

The paleocurrent directions determined by the cross-bedding and the ripples are the least efficient for modelling paleocurrents, as illustrated by the low values of K. Bluck (1971) used composite samples of all cross-strata that occurred in individual point bars, and obtained vector resultants that approximately paralleled the channel trend at specific locations. The samples obtained by the present author were not as extensive, and actually constituted small point locations. While the data of Bluck (1971) clearly illustrates the strength of the composite samples of cross-bedding, a relict environment may not provide entire point bar assemblages for paleocurrent analysis. In fact, the restricted extent of cross-bedding may be the product of post-depositional reworking of sediment. The composite samples that have been obtained by Bluck (1971), may in actual fact define the directional attributes of the point bar as a morphological feature, since the composite sample will reflect all of the primary and secondary components of flow at a channel section, whereas, the individual paleocurrent directions as defined by point samples will reflect much smaller-scale flow phenomena at very specific locations. The paleocurrent information that has been obtained by the author may be a reflection of the amount of data that would be available for study in relict environments.

Allen (1966) has stated that cross-strata are reflections of the progradation of bed material as a result of the interaction of primary and secondary flow directions. Unless one can determine whether cross-strata have prograded in response to transverse, oblique, or downcurrent flow directions, at specific points, then the utility of cross-bedding for modelling paleocurrent directions becomes questionable.

In Highland Creek, cross-stratification is largely restricted to the interiors of point bars. If only small portions of each point bar assemblage are preserved, the efficiency of cross-bedding for modelling paleocurrents will be low, especially for flashy channels.

Ripple marks are expected to be the least-efficient paleocurrent indicators. While within-site variance is low for ripples, the between-site variance is high. The ripples are residual bed features that respond to micro-scale perturbations in the flow, at the bed surface. Thus, the directional properties of the ripples need not be any reflection of general flow patterns (Allen, 1966). The low preservation potential of ripples, and the absence of micro-cross-strata in the Highland Creek deposits suggests that such small-scale bedforms are of little value in the determination of flow directions of Highland Creek, and possibly of flashy channels in other locations.

It is noted that the utility of the aforementioned paleocurrent indicators is dependent on the number of samples taken. The author would dispute the utility of any of the above paleocurrent indicators if the rankings are based on single sample sites. The significant between-site variance of all sample groupings is supportive of such a conclusion.

Ranking of Paleocurrent Data by Vector Resultants

The preceding discussion dealt with the ranking of individual sedimentary structures, as paleocurrent indicators, as determined by the statistical analysis of the directional data. This section is devoted to the ranking of paleocurrent phenomena for modelling the flow directions at the study site an Highland Creek.

The ranking of data by vector resultants is essentially comparative, since the valley and channel directions serve as reference directions with respect to the small-scale bed features (Figure 24). The ranking is based on the comparison of grand vector resultants of the cross-bed, ripple, imbricate, fabric, channel, and valley directions; and the variability of the small-scale features.

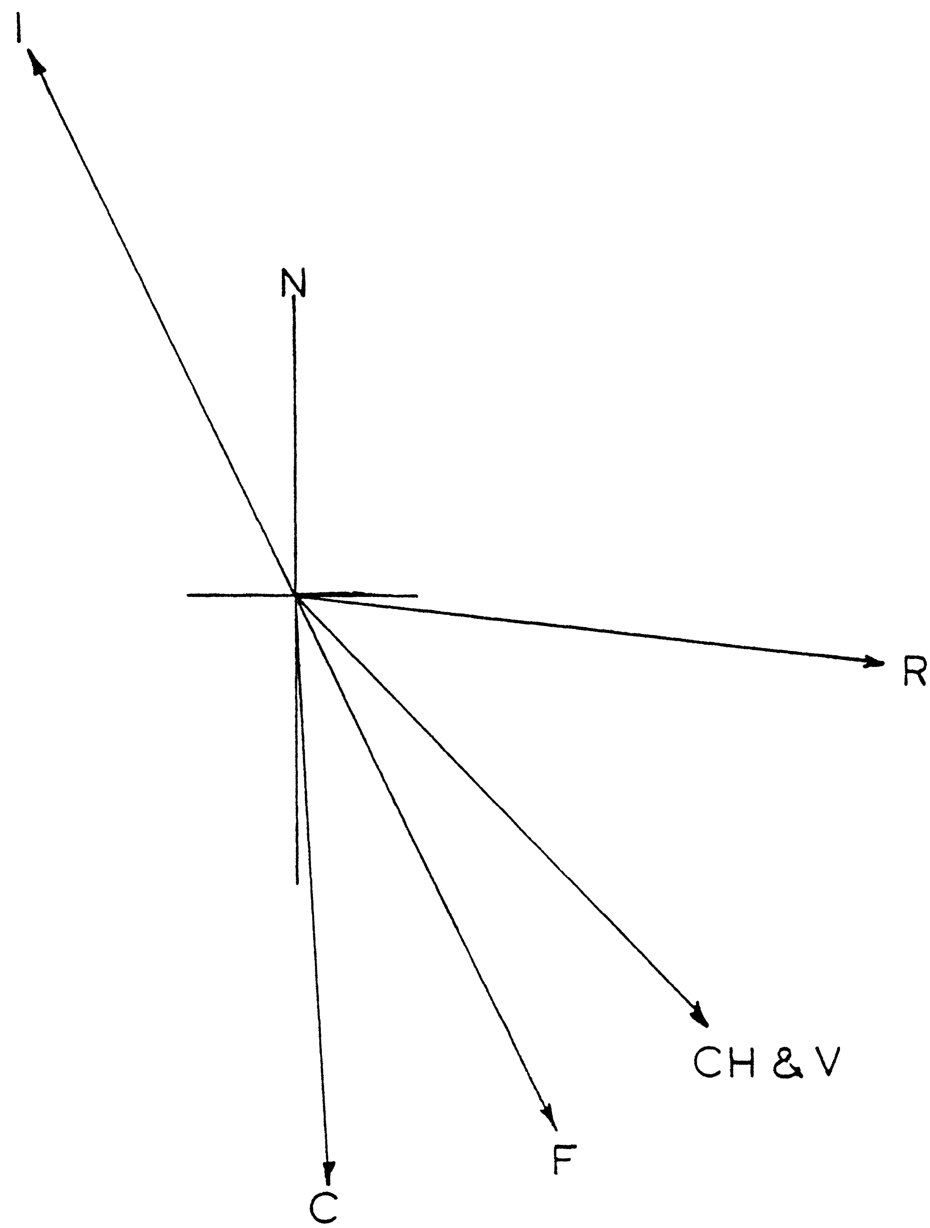


FIGURE 24. The schematic diagram illustrates the relationship between the flow directions as inferred from the channel and the valley form, and the sedimentary structures. The imbricates display the strongest parallel to flow directions and are probably the best paleocurrent indicators from the sedimentological information.

I - Imbricates
F - Fabrics
C - Cross-strata

R - Ripples
CH - Channel
V - Valley

The valley trend has been selected as the reference indicator of flow direction. The influence of primary and secondary flow components, geological and other environmental factors are reflected in the valley form and orientation. The orientation of the valley was determined by measuring the azimuth of the longitudinal axis of the feature, from topographic maps.

The channel form has been ranked as a first order directional indicator, because the vector resultant possesses the same azimuth of the valley. Individual azimuths are derived by measuring the orientation of a tangent to the mid-channel longitudinal section. Singular channel azimuths deviate from the valley trend. The first order ranking in this case corresponds to the first order ranking of the channel by Allen (1966).

From Figure 24 it would appear that the orientation of the grand vector resultants of the fabrics and the imbricated cobble discs are reasonable approximations of the true flow direction. The difference between the grand vector resultant for the fabrics and the channel and valley directions is about 17°. The difference between the grand resultant of the imbricates and the valley and channel directions is 163°. Therefore, the deviation of the imbricate grand resultant is 17° from the parallel-to-flow orientation. The author has ranked the fabrics and the imbricates as second order paleocurrent indicators.

In relict or fossil fluvial environments, in which the presence of gravel bedding, and in particular bed armour surfaces can be identified, fabric and imbricate orientations may be the best indicators of paleoflow directions, especially if the paleochannel or the valley cannot be identified.

The small-scale bedforms and sedimentary structures possess orientations that deviate significantly from the channel and valley orientations. The grand vector resultants of the cross-strata and the ripple marks deviate by 40° from the valley trend.

The cross-strata and ripple marks are difficult to rank in the hierarchy. Allen (1966) has indicated that small-scale bed features respond to primary and secondary flow components. Cross-strata record the direction of progradation;however, it may be virtually impossible to determine whether the bed features have responded to downcurrent or transverse flow components, without the aid of a more reliable reference. The directional properties of the cross-bedding are site-specific. That is, the cross-strata record flow directions that may deviate significantly from the general flow trend.

Ripple marks are responsive to the micro-scale characteristics of the flow and therefore, do not reflect the main flow directions (Allen, 1966). The smallest bed features may be of little value in the modelling of general flow directions.

Conclusions

The paleocurrent data presented above serves to illustrate the link between the bed configuration, facies, and flow direction in a flashy channel. All of the directional indicators and the individual samples yield vector resultants that deviate from random distributions. In many of the examples the vector resultants possessed high magnitudes.

From the analysis-of-variance, the fabrics represent the strongest paleocurrent indicator, as based on the concentration parameter K, about the grand vector resultant. The imbricates probably represent the second best paleocurrent indicator because of the precision estimates of the between-site, within-site, and the total population variance. Fabric orientations should be used in conjunction with imbricate directions or other more efficient directional indicator, due to the multi-modal nature of fabric distributions. The cross-bed and ripple orientations represent the weakest paleocurrent indicators, because of the low values of the between-site, within-site, and the study site precision estimates of the population variance.

The paleocurrent data can also be ranked by using the grand vector resultants as a comparison with the trend of the valley and the channel. The channel represents the best directional indicator, since the vector resultant of the channel azimuths parallels that of the valley trend. The fabric and imbricate grand resultants have been grouped together as second order directional indicators. The grand vector resultants of the fabrics and the imbricates deviate by 18° from the valley trend. The small-scale bedforms and sedimentary structures, for example, cross-strata and ripple marks are not very efficient indicators of flow direction, especially as derived from point locations.

CHAPTER FIVE

CONCLUSIONS

The sedimentological features observed at the study site on Highland Creek may be valuable in the reconstuction of relict fluvial environments. However, additional data are needed on bedform associations and paleocurrent directions, specifically as they relate to the study of flashy alluvial channels.

The preceding discussion yields several relationships between the conditions of flow in Highland Creek and the cohesionless sediments that form the most prominent bedforms and sedimentary structures. The attributes of the channel can be summarized as follows:

A. The hydrologic and hydraulic data illustrate the extremes that may occur between low flow levels and high magnitude flow events, and the relative rapidity with which the changes occur.

B. The sedimentary structures and textural attributes of the sedimentation units relate to specific phases of sediment transport, under progressively decreasing energy levels, during a recent high magnitude flow event. The coarse facies are representative of sedimentation during the early phases of falling-flow stage, and the finer facies are indicative of deposition during the latter phases of a falling-flow stage. The physical scale of the largest macroforms necessitates aggradation and progradation during high magnitude flow events.

The fine facies are deposited after gravel deposition has taken place. The rapid decrease in flow energy, and bed lag prevent the preservation of small-scale bedforms. The bedform associations that have been recognized in Highland Creek are related to the latter stages of a dynamic event.

C. The armoured bed surfaces of the channel are believed to be representative of selective erosion during the falling-flow stages of an event. The lower bar platforms that are found on the channel side of the point bars are characterized by low profile armoured surfaces. (The lower platforms are related to intermediate flow levels, McGowen and Garner, 1970; Bluck, 1971). The armoured configuration is interpreted as being the equilibrium bedform. The recurrence of lag surfaces even as sporadic and sparsely preserved features in the various deposits is suggestive of its stability. If the form were not stable under various flow conditions, then its persistence in the stratigraphic record would not result. The only examples of lag surfaces were found within riffle bars, especially at C-C.

The problem of identifying erosional surfaces in the coarse sediments, and the occurrence of lag deposits in riffle bars, may be resolved through the analysis of sediment transport and sedimentation patterns within the sinuous channel or any other channel pattern. The author noted above that the preserved armoured surfaces were restricted to interiors of the riffle bars. Comparable features are absent from the structural components of the point bars, except where coarse sedimentation units were covered by fines. Leopold and Wolman (1957, 1960) and Bluck (1971) state that the pool zone of a bend is characterized by bed scour during peak flows, whereas the riffle zone is marked by deposition. The reverse occurs at low flow. The field evidence indicates that armoured surfaces are more likely to be preserved in the riffle bars by burial during bed aggradation. The discontinuous nature of the armoured beds is probably related to bed scour during the early phases of a high-flow stage event as rising waters cover the surface. The selective erosion of the bed would be dependent on the instantaneous tractive forces, turbulence, and ultimately the stability of the bed itself. From the studies of Lane and Carlson (1954), Sundborg (1956), and Johansson (1965, 1976), it has been shown that the most stable bed surface in gravels is that which is formed of imbricates and prolate clasts that are oriented parallel-to-flow. The preserved surfaces found at the site are formed of such fabric structures, although clasts oriented transverse- and oblique-to-flow occur in relative abundance.

As an alternative to the preceding statements, it is entirely conceivable that the bed armouring processes can be attributed to rising-flow stage, as surfaces become submerged. The increasing severity of flow may remove fines, prior to the burial of the lag surface. Bed scour would not necessarily have to destroy a lag surface. The lag surfaces may therefore be representative of the limits of bed degradation prior to rapid burial. The author believes that the burial rates would have to be rapid, otherwise bed scour would destroy the surfaces, or fine material transported near the bed would have become trapped in the pore spaces between the cobble clasts, and obscure the fabric of the lag deposits.

The bed armour deposits in the pebble and cobble gravels are being used in this project as indicators of erosional and depositional surfaces. The nature of the formative processes are clear enough; however, it is impossible to ascertain the interval of time over which the processes are active. That is, armouring could occur during the initial phases of the rising-flow stage as surfaces become submerged, or during falling-flow stage, or possibly during both phases. Therefore, the last statements imply that more than one lag surface may be identified with the same flow event.

D. The bedforms cannot be assembled into associations that are based on continuous flows, or on flows that experience sustained high-flow stage. The rankings of bedforms can be achieved in a dynamic sense, so that phases of an event are identified with the characteristic bed configuration.

The small and moderately sized bedforms are regime sensitive, and may only be recognized in continuous flows or in flows characterized by sustained high flow and sediment movement. Such features can be found in Highland Creek, although their presence can only be associated with the latter phases of sediment movement during an event.

The largest macroforms are most likely preserved, since they are relatively insensitive to the dynamics of the flow. The association of macroform on macroform is easily identified from Highland Creek. Such features are not uncommon in other types of alluvial channels (continuous flows), although in many cases smaller-scale bed features are also found in relative abundance.

E. Paleocurrent directions as derived from bedforms and sedimentary structures yield vector magnitudes and population variances that differ between structural types. Generally the orientation of imbricated cobble discs provided the strongest paleocurrent indicator. The fabric data indicated reasonably strong vector resultants, and high concentration values, although the between-site and within-site variances suggest that the fabrics would be inaccurate flow direction indicators at specific sites. Cross-bed and ripple data indicate that these features are weak paleocurrent indicators, as based on the results of the analysis-of-variance.

F. The directional attributes of the imbricates and the fabrics are difficult to assess in terms of depositional or post-depositional origins. Bed armouring processes, obstructions on the bed, and other forms of post-depositional modification may alter the primary fabric. For the most part the author regards the surface fabrics as being of post-depositional origin, possibly due to bed armouring. The internal fabrics of the gravel bedding demonstrate non-preferred orientations. This characteristic is attributed to rapid transport, grain-to-grain collisions, and rapid sedimentation and burial. The latter case is an illustration of a primary fabric.

G. The formulation of paleocurrent hierarchies resulted in two different groupings. The large-scale valley and channel trend are representative of the best paleocurrent indicators, since the totality of the flow characteristics are reflected in the channel pattern and the valley form. Gravel fabric and imbricate directions represent the second order paleocurrent indicators. The ranking was based on a comparison of grand vector resultants.

The sedimentary structures and bedforms were ranked statistically, as based on the concentration parameter K about the grand vector resultants for each of the sample groupings. The statistical ranking constitutes the second grouping of paleocurrent indicators.

The small-scale bedforms and sedimentary structures are apparently inefficient paleocurrent indicators, at least as derived from small point locations. The grand vector resultants of the cross-strata, and the ripples deviate by 40° from the trend displayed by the valley.

H. In the absence of data derived from the channel and valley directions, the best general paleocurrent indicators are the imbricated cobble discs, as demonstrated statistically, and based on the high preservation potential of the form.

APPENDIX I

Part A : Definitions of Hydraulic Variables

The values specified in Table (II) are derived from standard or accepted physical relations. The following is a listing of the variables and the defining functions.

$$Fr = \frac{U}{\sqrt{gd}} \quad (12) \qquad U = \frac{1}{n} R^{2/3} S^{1/2} \quad (13)$$

$$Re = \frac{Ud}{\nu} \quad (14) \qquad n = 0.01312\ D^{1/6} \quad (15)$$

$$\tau = \gamma RS \quad (16) \qquad U* = \sqrt{\tau/\rho} \quad (17)$$

Qs = sediment discharge (T/sec)

where d = depth

D = representative grain size D_{35} as defined by Strickler (see Raudkivi, 1976)

g = gravitational acceleration = 9.807 m/sec^2

R = Hydraulic Radius ≐ dm

S = slope of the energy gradient

U = flow velocity (m/sec)

U* = shear velocity (m/sec)

γ = specific weight of water ≐ 1.00Kg/m^3

ν = kinematic viscosity of water ≐ 0.01cm/sec

τ = shear stress

APPENDIX I

Part B : Bedload Function and Variables

The sediment discharge for Highland Creek was determined from the Meyer-Peter and Müller (1948) bedload function. The formula is

$$\frac{(K/K')\ R_k S}{(\gamma_s - \gamma)\ d} - 0.047 = 0.25 \frac{\rho^{1/3}}{(\gamma_s - \gamma)\ d} \left(qb \frac{(\gamma_s - \gamma)}{\gamma_s}\right)^{2/3} \quad (18)$$

where d = mean grain size defined by $\Sigma pi \Delta di$ (m)

$K = 0.4/R^{2/3}\ S^{1/2}$

$K' = 26/(D_{10})^{1/6}$ (Meyer-Peter and Müller used D_{90}. In this case $D_{10} = D_{90}$ of Meyer-Peter and Muller since the grain size distributions are reversed.)

R_k = Hydraulic radius = $\frac{A}{P}$ where A = cross-sectional area, P = wetted perimeter

S = slope = 0.006

γ = specific weight of water $\doteq 1.000 T/m^3$

γ_s = specific weight of sediment $\doteq 2.65 T/m^3$

ρ = mass density of water $\doteq 0.102 T\text{-}sec/m^4$

qb = sediment discharge per unit width = t/sec/m

Section A-A		Section B-B	
S	= 0.0060	S	= 0.0060
d	= 0.0069	d	= 0.0074
D_{10}	= 0.0420	D_{10}	= 0.2080
K	=11.5400	K	= 9.4600
K'	=44.1000	K'	=33.7800
R_k	= 1.2970	R_k	= 0.9030
Qs	= 0.00936 T/sec	Qs	= 0.0026 T/sec

APPENDIX I

Part B cont'd

Section 2-2		Section C-C	
S	= 0.0060	S	= 0.0060
d	= 0.0079	d	= 0.0042
D_{10}	= 0.0970	D_{10}	= 0.4160
K	= 10.2000	K	= 8.8600
K'	= 38.6000	K'	= 30.1000
R_k	= 1.4300	R_k	= 1.5700
Qs	= 0.0055 T/sec	Qs	= 0.0110 T/sec

The data listed immediately above are the estimated hydraulic parameters used in the calculation of bedload discharge during high flow stage events.

APPENDIX II

Grain Size, Summary Distribution

Sample	M(ø)	(σ)	Sk	Ks
A-1	-1.320	1.350	0.75	0.70
A-2	2.220	0.550	0.02	1.06
A-3	-0.460	1.790	0.23	0.87
A-4	-0.690	1.820	0.01	0.83
A-A-1	1.430	0.890	-0.05	1.16
A-A-2	0.200	1.820	-0.35	0.99
A-A-3	-0.050	1.720	0.23	0.81
A-A-4	-2.320	2.840	0.45	0.57
A-DT	2.950	1.250	-0.31	2.73
A-DF	2.230	0.610	-0.76	1.07
A-A C	-2.780	2.580	0.39	0.72
B-B-1T	-1.930	2.790	0.26	0.77
B-B-2	-0.550	2.430	-0.13	0.71
B-B-3	-1.470	2.390	0.21	0.74
B-B-4	-3.100	2.600	0.31	1.04
B-B-DG	-3.580	3.510	-0.05	0.80
B-B-DS	1.550	1.920	0.15	1.66
B-BII-1	1.910	0.740	-0.40	1.52
B-BII-2	-0.500	2.670	0.22	0.62
B-BII-3	2.030	0.710	0.00	1.05
B-B-Cr	1.820	0.640	-0.64	1.16
B-B-r	2.580	0.900	0.95	1.41
B-BIII-T	2.630	0.770	0.07	1.01
B-BIII-F	2.410	0.700	0.02	0.98
E-E1-T	-1.530	2.510	0.36	0.69
E-E1-S	2.000	1.260	-0.41	1.78
E-E1-B	0.020	2.070	-0.18	0.74
E-E2-S	1.670	0.850	-0.21	1.19
E-E-2S	0.270	1.770	-0.36	0.88
E-E-3	2.550	0.630	0.06	1.13
E-E-4	1.770	0.090	-0.24	1.23
E-E-5	-4.350	3.770	0.33	0.86
2-2-1	2.190	0.630	0.35	1.18
2-2-2	2.870	0.790	0.08	1.15
2-2-MC	-3.320	2.890	0.21	1.14
2-2-r	1.410	0.580	-0.18	1.00

APPENDIX II (cont'd)

Sample	M(ø)	(σ)	Sk	Ks
CF-1	-2.500	3.610	0.44	0.66
CF-2	-1.880	2.840	0.52	0.66
CF-3	-1.680	2.850	0.48	1.10
CF-4	-0.080	2.650	0.01	0.69

APPENDIX III

Paleocurrent Azimuths

Sample	Measures				
Subhorizontal lamination					
A-A-D	200	215	259	240	194
16° dip	226	241	232	238	230
Chan. 143	246	247	231	249	248
	230	254	229	201	233
	226	204	217	239	
B-B-P	174	190	210	183	176
16° dip	132	136	181	204	107
Chan. 081	143	176	177	195	198
	191	188	193	176	173
	182	178	185	171	210
Cross- laminae					
IAB C-C-1	070	104	150	077	121
32° dip	126	136	148	143	156
Chan. 175	123	098	156	160	106
	117	092	110	097	103
	102	104	110	109	097
DRS C-C	112	142	101	118	148
30° dip	146				
Chan. 130					
IAB C-C-2	165	165	179	181	164
32° dip	153	170	155	161	165
Cross-beds Gravel					
A-A-MS	112	132	114	125	140
24° dip					
A-A-D	079	082	093	077	086
15° dip					
Ripple Marks					
2-2	210	142	179	224	173
Chan. 194	184	198	235	223	256
	249				

APPENDIX III (cont'd)

Sample	Measures				
Ripple Marks					
C-C-R1	158	158	147	171	209
Chan, 186	176	168	136	147	
C-C-Rh	046	118	013	117	047
Chan. 081	114	106	064	012	097
	023				
D-D-P	030	066	085	023	040
	077	111	102	005	001
	012	019	031	035	039
	027	052			
Linear Depressions					
2-2	220	219	190	227	245
	199	202			
Fabrics					
A-A-1	126	215	230	228	132
	164	146	151	196	096
A-A-2	138	249	242	256	204
	215	164	214	136	256
A-A-PB	230	191	269	137	134
	184	089	153	114	146
	129	168	136	258	146
	152	096	257	230	098
	164	126			
B-B-R	137	138	243	133	211
Chan. 194	114	205	195	216	173
C-C-S	200	195	096	107	231
	222	238	097		

APPENDIX III cont'd

Sample	Measures				
Fabrics					
Alt.Bar.	056	126	104	023	131
E-E	089	016	033	084	028
	134	063	003	059	028
	068	042	120	177	003
	059				
A-A-Int	070	027	190	090	109
	209	159	325	222	140
	232				
B-B-R2	104	132	266	109	200
	204	236	161	139	
Imbricated Cobble Discs					
B-B-i	027	062	032	340	005
Chan.194	331	009	332		
B-B-2	040	025	359	007	015
Chan.181	012	354	024		
E-E-1	314	304	316	296	329
Chan.125	274	331	336	259	
E-E-2	316	296	250	321	254
	271	286			

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