BRAIDED STREAM SEDIMENTATION IN THE

SOUTH SASKATCHEWAN RIVER

BRAIDED STREAM SEDIMENTATION IN THE SOUTH SASKATCHEWAN RIVER

By

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ABSTRACT

In the study area, the South Saskatchewan River has a sandy bed (mean diameter .3 mm) with irregularly-shaped braid bars termed sand flats. These range in length from 50 to 2000 m. The river has an average discharge of 220 m^3/sec, with a mean annual flood of 1450 m^3/sec. The river has been dammed upstream of the study area since 1965, but little downcutting has occurred.

Ripples, sand waves and dunes are the equilibrium bedforms present. Ripples and dunes are well known, but sand waves are long, low bedforms with superimposed ripples, lack scour troughs, and occur at lower flow velocities than dunes. Foreset-type bars are also present, but are not equilibrium forms. They result from flow expansion around older topography. They occur at (1) channel junctions, (2) channel bends, (3) areas of channel widening, (4) places of vertical flow expansion. They deposit planar crossbeds.

Large areas of the river have many sand flats with no major channels, and may even lack minor channels. These areas are termed sand flat complexes. Where a major channel curves around a sand flat complex, a large diagonal bar is deposited. It is mainly on the tops of these bars where new sand flats form.

The major channels rarely exceed 5 m in depth, but may be 150 m wide. They are floored by sinuous-crested dunes with sand waves and ripples along their margins. The dunes build up during floods (2 m maximum amplitude). Larger dunes occur in the deeper channels.

Three different morphologies of small sand flats, symmetric, asymmetric and side, have been recognized. Each type forms from a bar which becomes partly immobilized where it becomes emergent. The remainder of the bar front continues to advance around this emergent nucleus. The different morphologies result because of the control exerted by pre-existing deposits on the shape of the initial bar.

Larger sand flats lack these morphologies because they have been extensively modified. The major processes of modification are vertical, lateral, and upstream accretion by bars; linking of sand flats by bars; erosional action. The variable morphologies of larger sand flats reflect only their latest modification. The stratification of sand flats is mainly planar crossbed sets deposited by the bars.

During the winter, a 60 cm thick layer of ice covers the entire system. The sand flats are immobilized because their top layers of sediments are frozen. In some places, their surfaces are disrupted by fluid escape caused by high pore pressures generated by freezing. Flow proceeds down the channels under the ice. Rafting of cobbles and scouring around grounded ice blocks takes place at breakup.

The facies sequences resulting from sedimentation in the river are mainly sandy. Those which are deposited by channels consist dominantly of trough crossbeds, but lone planar crossbed sets may be present, deposited by large bars. Facies sequences which include sand flat deposits have several sets of planar crossbeds stacked on top of one another. All sequences have a zone of small crossbeds and ripple cross-lamination near the tops, resulting from shallow water deposition. They are capped by one-half metre of muddy flood-plain deposits.

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CHAPTER 1

THE SEDIMENTOLOGY OF BRAIDED RIVERS AND THE CONTRIBUTION OF THIS STUDY

INTRODUCTION

Alluvial rivers may be meandering, braided, or straight in plan view. Although straight rivers are less common than the others, each type exists in nature on widely varying scales, from streams a few metres wide to rivers tens of kilometres wide, draining landmasses of continental proportions. This thesis concerns a braided river intermediate in size between these two extremes. A braided river is one flowing in several dividing and reuniting channels, the cause of division being obstruction by sediment deposited by the stream (American Geological Institute, 1957).

Although the fundamental causes of braiding are poorly understood, several conditions present in many natural streams promote braiding:

1) high rates of supply of sand-to-gravel-sized sediment;
2) easily erodible non-cohesive banks;
3) rapid, high-magnitude changes in discharge;
4) high regional slopes.

High rates of supply of coarse sediment contribute to the inability of the stream to transport all of its load, particularly at lower stages. Easily erodible banks allow the stream to adjust laterally to the presence of mid-channel bars. Rapid, high magnitude discharge fluctuations cause variations in the ability of the stream to transport sediment, and also contribute toward instability in stream banks. On rising stages, banks are commonly undercut, and on falling stages, drainage of water from bank sediments may cause slumping. High regional slopes enable streams to transport coarse sediment and to erode banks during periods of high discharges. Rivers which satisfy two or three of these conditions may be braided.

Braided rivers are common in periglacial and semiarid environments. In both, physical weathering provides large amounts of coarse clastic sediment. Discharge fluctuations occur in periglacial areas because of seasonal and diurnal temperature variations. In semiarid environments, intense storms cause flash floods, partly because of the lack of vegetation which would otherwise moderate the rate of run-off. Braided rivers are not restricted to these environments, however. Rivers which drain young mountain belts may braid because of the large supply of coarse clastic detritus which they receive. In most of these cases, seasonal snowmelt in the mountains causes discharge fluctuations of major proportions. Rivers which flow through areas where large amounts of unconsolidated sand and gravel are present may braid. In this case, braiding is a response to the amount of coarse sediment supplied.

Braiding, therefore, is apparently the result of the inability of a river to transport all or part of its load at lower stages. Channel division increases the ability of a river to transport large amounts of bedload (Leopold et al, 1964). If the bedload transport rate of a braided stream is (on the average) the same as the rate of sediment supply, then the stream may approach equilibrium while maintaining a braided pattern.

BRAIDED RIVERS - THE STATE OF KNOWLEDGE

Despite the fact that much is known about specific braided streams, few generalities about them can be inferred at the present time. Smith (1970) has shown that a proximal to distal trend from a gravelly to sandy bed exists in the Platte River system. The grain size change is accompanied by a change in bar type from longitudinal bars to foreset-type transverse bars. Boothroyd (1972) has extended the concept of this trend to more proximal environments with steeper slopes and coarser grain sizes. Although in nature a continuous gradation exists between the two types, sandy and pebbly systems will be treated separately here.

Pebbly Braided Streams

This review of pebbly braided stream studies will be brief because many of these are not directly related to the subject of this thesis. The main part of the review will be presented in table form containing the important points or theme of each paper. After the table, the major trends in the research will be discussed.

TABLE 1

A REVIEW OF PEBBLY BRAIDED STREAM STUDIES

Author	Year	Main Points or Theme
Leopold and Wolman	1957	An excellent discussion of the fundamental hydraulics and processes of braiding. Braiding results from a stream becoming incompetent to transport part of its load. The lag deposit formed becomes a nucleus for mid-channel bar growth.
Doeglas	1962	An early description of two braided streams and some resulting stratification. Fluctuations in river stage were shown to be responsible for the deposition of silts in cut-off channels.

TABLE 1 (Continued)

Author	Year	Main Points or Theme
Krigstrom	1962	A very good descriptive treatment of a braided system which introduces the term spool bars. Many of the bar morphologies and processes described here appear in later studies.
Fahnestock	1963	By time lapse photography, the very rapid shifting of shallow channels in a steep proximal system was demonstrated. Antidune forms on the water surface were described from some channels.
Ore	1963	Pebbly longitudinal bars were interpreted as resulting from the deposition of the coarsest bedload fraction. These bars had discontinuous horizontal stratification internally.
Williams and Rust	1969	A very complete description of a coarse grained braided system in terms of facies from channel bottom to floodplain.

TABLE 1 (Continued)

Author	Year	Main Points or Theme
Smith	1970	Pebbly braid bars were present in the proximal portions of a braided river. The internal structure of a bar was crude parallel stratification.
McDonald and Banerjee	1971	Channels were described in terms of pools and riffles. Regularly spaced ridges of large clasts on the riffles were termed transverse ribs, and interpreted as equilibrium bedforms.
Rust	1972	The internal structures of pebbly braid bars were shown to consist of poorly defined horizontal stratification. A hypothesis for bar development is advanced, involving accretion at the upstream end and erosion at the downstream end, resulting in upstream migration.

TABLE 1 (Continued)

Author	Year	Main Points or Theme
Boothroyd	1972	A well-illustrated study which incorporates description of the system, along with hydraulics of sediment transport. Sedimentary structures are particularly well illustrated.
Church	1973	A hydraulic analysis and quantitative description of a braided system, but few real advances.
Fahnestock and Bradley	1973	A contrast is drawn between a steep high energy braided stream with another on a lower slope subject to glacial breakout floods. In the former river, rapid lateral channel shifting occurs, but in the latter, change is slow at normal stages.
Bluck	1974	A model is presented for the lateral growth of a bar on the back of a riffle. An attempt is made to understand the relationships between bars in a complex braided system.

TABLE 1 (Continued)

Author	Year	Main Points or Theme
Gustavson	1974	A descriptive treatment of a pebbly braided river. The internal stratification types of bars, pools, and riffles are documented.
Hein and Walker	in press	A model is developed for the growth of some bars from diffuse gravel sheets. These ceased to move, becoming a lag deposit around which the bar grew.
Boothroyd and Ashley	1975	Downstream changes in sediment size, bar morphology and processes are documented from a very proximal outwash fan.
Church and Gilbert	1975	An extensive discussion of the hydraulics of braiding, along with a quantitative description of many aspects of braiding.

Much of the early work (Doeglas, Krigstrom and Fahnestock) was directed towards general description of pebbly braided streams. This is a necessary step in the investigation of any sedimentary environment. Leopold and Wolman's work was exceptional for its time, in that a hydraulic explanation for braiding was attempted. Little progress has been made along this line of research for at least fifteen years.

Williams and Rust (1969) continued the descriptive trend, but utilized a facies approach. Smith's work (1970) was essentially descriptive, but internal structures were investigated, unlike most earlier studies.

After this point, few studies were directed towards a simple description of a braided system. Later work concentrated on specific aspects such as transverse ribs (McDonald and Banerjee, 1971), or on developing models for bar growth (Rust, 1972; Smith, 1973; Hein and Walker, in press). Another trend which was taking place was an increase in hydraulic investigation (Church, 1972; Hein and Walker, in press; Boothroyd and Ashley, 1975).

The trend of the research can be summarized as proceeding from general description to concentration on specific aspects while at the same time attempting to generalize from those specific aspects.

Sandy Braided Streams

Large sandy braided streams appear to be less common than pebbly systems; as a result, there is a smaller body of literature dealing with them. In contrast to pebbly streams, sandy braided rivers are competent to transport most of their load at most discharges. Therefore braiding is not due to incompetency, but results from over-supply of sediment, i.e., incapacity (Coleman, 1969). Sandy braided streams, being more distal (Smith, 1970) commonly have lower slopes and less flashy discharges than pebbly systems.

Because of the diversity of the types of sandy braided rivers reported in the literature, each will be reported separately. It is not yet possible to integrate all the data collected in the different studies into a coherent model.

Some of the general conclusions of Leopold and Wolman (1957) are as applicable to sandy as to gravelly streams. The presence of a central bar, whether sand or gravel, causes the channel slopes to be greater than in the single channel case. The presence of the bar also causes erosional attack on the banks, promoting widening of the channel.

Chien (1961) has reported on the lower Yellow River, a sandy to silty river in China with very high sediment concentrations. Along its course, the river alternately converges and diverges. In the narrow reaches, it is deeper with few braid bars, in contrast to the wider reaches, where many shallow channels and sandy braid bars are present. The narrow reaches result from clay plugs in the floodplain, unerodible cliffs, or river regulation work. Chien documents changes in locations of the channels, relating this to deposition in one part of the system resulting in progressive diversion of flow to lower parts of the river system.

Brice (1964) published air photos of the Loup River showing sandy diamond-shaped braid bars. He concluded that the effect of braiding on a wide channel is to render it hydraulically similar to a narrower single channel.

Sandy transverse foreset-type bars were described first by Oré (1963). Trenches in these bars revealed planar cross-stratification with highly variable paleocurrent directions.

The Brahmaputra River in Bangladesh is the largest sandy braided system yet studied (Coleman, 1969). By the use of air photos and extensive sampling, Coleman has analysed several hundred years of the river's history. This provides the most complete understanding yet achieved of how braided river systems change through time, and therefore of the relationships between the active environment and the preserved deposits.

The river shows lateral expansions and contractions with most braid bars present in the wider reaches. At low stages, the river is choked by rhomboid-shaped sand and silt bars up to 11 km long, but these are commonly destroyed or modified at flood stages. Echo sounding during high stages has revealed repetitive or periodic bedforms ranging in amplitude up to 15 m. Repetitive or periodic bedforms are those which recur several times in a downstream direction, in some cases with a regular spacing. Coleman classified these on the basis of height as ripples, megaripples, dunes or sand waves. The class boundaries were arbitrary, corresponding to no natural divisions. The floodbasins of the river accumulate up to 4 m of peat and fine mud, but it is unclear how much of this is likely to be preserved. The sand body accumulating in the channel near these overbank deposits is about 30 to 50 m thick, so the proportion of floodplain material is very low, a common characteristic of braided systems.

Collinson (1970) worked on the Tana River in Norway. The river deposits consist of: 1) vegetated banks and islands; 2) large areas of exposed sand which are complexes of smaller bedforms; 3) repetitive en-echelon linguoid bars which commonly have smaller bedforms superimposed on them; 4) dune covered areas in the channels and on the backs of the linguoid bars; 5) areas of low stage ripples. Collinson observed that the linguoid bars were inactive at low stage, and because of their large size, they diverted the flow around themselves. During exposure, these bars were commonly modified, with erosional rounding of the slipface creating low angle surfaces. When the bars began to readvance during the next high stage, a reactivation structure was formed. No hydraulic research was carried out in this study, so data is incomplete on the linguoid bars and the other bedforms in the river. Collinson (1971a) showed that the smaller, low stage bedforms possess a higher paleocurrent dispersion compared with the larger, high stage bedforms. A study of the river during the spring ice breakup revealed ice drag marks and scours created around grounded ice blocks (Collinson, 1971b).

The Tana appears to be very much like the South Saskatchewan River, judging from published air photos (Collinson, 1970). Specific parts of the Tana study will be referred to throughout this thesis.

Smith (1970) showed that the Platte River is floored by transverse foreset-type bars and dunes in the channels. The transverse bars are wide, flat-topped, periodic or solitary wedges of sediment with ripples, dunes, diminished dunes, or plane bed superimposed on their backs. Many of the solitary bars are localized by the geometry of the situation, i.e., at channel junctions, while the repetitive forms and the solitary mid-channel forms are independent of the local geometry. The repetitive forms strongly resemble the linguoid bars of the Tana (Collinson, 1970). Smith regards both the solitary and repetitive types to be the same, but this may not be true. This question will be dealt with more thoroughly in Chapter IV of this thesis.

In a later report on the same river system, Smith (1971) elaborated more fully on the development of transverse bars. He showed that they assumed a symmetric lobate shape where their development was unobstructed. Distortions of this shape were caused by: 1) proximity to stable banks; 2) adjacent strong currents; 3) unsteadiness of flow with dissection of the bar; 4) irregular basin depth. Smith demonstrated that there is a relationship between the discharge over a bar and the active surface area of the bar. If the total area of the bar exceeds the active area, the bar may become irregularly shaped due to dissection.

Smith (1972) also showed that the laminations in transverse bars were produced by the avalanching of small bedforms over the front of the bar. The sorting which is responsible for the laminations takes place in these small bedforms on the top of the transverse bar.

Few consistent trends can be discerned in the literature on sandy braided streams, partly because of the small number of papers on the subject. One important advantage possessed by investigators of sandy systems is that the bedforms developed in sand are relatively well understood, compared with those in gravel. This results mainly from experimental studies in which sand is almost always used (Gilbert, 1914; Simons et al, 1965; Southard in Harms et al, 1975).

AREAS OF INSUFFICIENT KNOWLEDGE ABOUT SANDY BRAIDED STREAMS

A facies model is a summary of the important processes and deposits in a sedimentary environment. The formulation of a facies model is somewhat subjective, and depends on the definition of the environment, the type of data collected, and the means by which the data are integrated.

In order to advance towards the development of a facies model for sandy braided rivers, it is necessary to understand the processes and deposits of specific streams. As the literature review has shown, some sandy braided rivers have been studied in detail, but several areas of insufficient knowledge remain. The major deficiencies are: a) incomplete definition of subenvironments; b) inadequate understanding of major processes; c) a lack of knowledge concerning interactions between major elements in braided rivers; d) a degree of confusion about the types of bars in different systems; e) a shortage of data on the internal stratification of the deposits. Each of these areas of deficiency will be discussed individually.

(a) Definition of Subenvironments

To define adequately all of the subenvironments of a system, a detailed description of the entire system must be made. Essentially only one report (Coleman, 1969) attempts to describe all the subenvironments of the river system being studied. Other reports are selective, with little attention paid to major portions of the systems. For example, the large exposed areas of sand noted by Collinson (1970) were never described. Smith (1970, 1971) did not describe the floodplains of the Platte, even though these were mentioned. These examples serve to illustrate that another description of a sandy braided river would not be repetitive; indeed, it will form part of the vital factual basis of the study.

(b) Processes in Sandy Braided Streams

Although most of the studies cited in the literature review have contributed towards the understanding of the processes in sandy braided rivers, many gaps in knowledge remain. The processes which are responsible for building large scale sand bodies present in the Tana and Brahmaputra Rivers are unknown.

Some of this inadequacy stems from a single cause: great difficulty exists in observing processes when they are most efficient, i.e., at flood stages. During these times, rates of erosion, transport and deposition may be very high, with the flow achieving its greatest ability to remould its bed. High flood stages on most braided rivers cover the bars with varying depths of fast moving, turbid water, making direct observation impossible. Therefore, high stage processes commonly must be inferred from observations before and after the flood event.

(c) Interactions Between Major Elements in the System

It is not clear from the literature how major elements in the systems such as channels and bars interact with one another. This is important because the presence of pre-existing braid bars probably influences to a great extent where new braid bars will begin to form in the channels. It is not clear whether a bar begins to grow in a previously widened area, or the formation of a new braid bar causes erosion of surrounding bars.

The controls on the locations of formation of braid bars have never been adequately documented in the literature. Chien (1961) and Coleman (1969) have both stated that braid bars form in wider reaches where the streams shallow and expand laterally. The effects of other major obstructions to quasi-uniform flow such as vegetated islands, major river bends, and bars stabilized by vegetation are unknown.

(d) Bar Types

Several different structures have been described as the braid bars of the different systems. Coleman (1969) described sand bars up to 11 km long in the Brahmaputra; presumably these are complexes of smaller structures. Collinson (1970) described repetitive, slipface-bounded wedges of sediment in the channels of the Tana River, terming them linguoid bars. He considered these to be the important braid bars of the system, neglecting the exposed sandy areas which he termed modified linguoid bars. Smith (1970) described transverse bars, slipface-bounded wedges of sediment which may be either repetitive or non-repetitive. Many of the non-repetitive forms are localized by the geometry of the situation, i.e., at channel junctions. The repetitive or solitary mid-channel forms strongly resemble Collinson's linguoid bars.

The braid bars of each of the authors, even allowing for different terminologies, are different structures. The relationships between the types of bars in the different systems are unknown.

(e) Internal Stratification

Although most investigators have reported some details of stratification, few systems have been thoroughly studied in this respect. A major reason for this is that the collection of stratification data is time-consuming, difficult and in some cases virtually impossible. Box coring in deep, fast-moving water is impractical in most cases because of scouring around the corer. However, channel sediments may be investigated if the box coring is done at periods of very low flows which are present in some systems.

The stratification patterns of some small sandy braid bars are adequately known (Smith, 1972). However, for the large, complex forms illustrated by Coleman (1969), little data exist. Collinson (1970) reported complex side bars, and large areas of exposed sand, but no stratification data were reported.

THE PURPOSES OF THE STUDY

General Purposes

This study was initiated after work on a Devonian sandy braided stream deposit (Cant and Walker, 1976) showed that knowledge about this type of modern river was inadequate in some respects. Because of this stimulus, one of the basic purposes of the present study is to collect data to facilitate the interpretation of ancient rocks. This is best accomplished by relating the processes in the river as closely as possible to the different facies of the deposits and their distribution.

Another of the general purposes is to document a previously undescribed sandy braided river so that it may be compared to others reported in the literature. This is of interest because the variations in form and process among streams of this type are not understood. In particular, the variation in bar types between systems is poorly understood, so investigation of the bars and the reasons for their formation is a prime purpose.

These general objectives were apparent before any work was started. They arose from consideration of the state of knowledge about sandy braided streams and the inadequacies in that knowledge.

Specific Purposes

Reconnaissance of the South Saskatchewan River showed how the general purposes could be translated into specific goals for the day-to-day field work.

Very large sandy braid bars are present in this system. They will be termed sand flats to distinguish them from the transverse bars also present in the river. A major objective is to investigate the controls on the formation of these sand flats, the mechanism of their formation, and their internal stratification and resulting facies patterns.

Because the sand flats form initially in the channels, it is necessary to attempt to understand the interactions between the sand flats and the channels. The morphologies of the channels and the bedforms in the channels were therefore investigated to attempt to discover where and why new sand flats formed.

The migratory bedforms in the system became another focus of investigation because they cover the floors of the channels. This involved determining what types of bedforms are present, the range of hydraulic conditions under which each type is stable, where each occurs in the system, how they react to different conditions in the river, and the stratification resulting from their presence.

Another specific purpose was to attempt to determine the reaction of the braided system to conditions which differ markedly from the average state in which the river is commonly observed. Some of these conditions are: 1) high flood stage; 2) very low stage; 3) periods of ice cover; 4) spring ice breakup. These events cause important changes in the system, and hence were investigated.

It was towards these specific goals that the day-to-day field work was directed; therefore, they served as a frame of reference for progress in the research.

THE METHODOLOGY OF THE STUDY

General Approach

In attempting to fulfill the purposes discussed, several different approaches were combined during the period of the fieldwork.

After a general reconnaissance, it became clear that detailed observations of changes in the system were necessary to understand the development of the large sand flats. Because of the size of the river, the entire braided section could not be studied in great detail: a reach typical of the braided section was therefore chosen for intensive study. Aerial and surface reconnaissance showed this 10 km long reach to be representative of the braided section. A very great familiarity with this study reach was developed so that any changes could be detected and understood in terms of the initial conditions and the processes which caused the changes.

Specific Methods

(a) Aerial Observation - In order to obtain a large scale view of the river, five flights were made over three summers, covering most of the braided section of the river. This was an efficient means of observing major variations along the river course in channel pattern, bar morphology, and other large scale features. Aerial observations, therefore, acted to check that the sand flats and channels investigated in detail were typical.

(b) Mapping - This was carried out on several different scales. A summary map (on a very large scale) of virtually the entire braided reach of the river was compiled from air photos. This map served to illustrate the shape of the river, the deflection of the major channels, and the larger areas of accumulation of sand.

On a smaller scale, a summary map of the study reach was prepared by tracing air photos to make a base map, then drawing on this the present day sand flats. The resulting map was accurate enough to use in the investigation of the relationships between channels, sand flats, and islands.

On a very local scale, sketch maps or pace and compass maps were made of individual sand flats. These were prepared to investigate sand flat morphologies, distribution of bedforms, and types of processes which formed each individual sand flat. Many of the sand flats were remapped after high flood stages altered them. Because direct observation was impossible, comparison of the maps prepared before and after the flood events gave a better understanding of the high stage processes than would otherwise have been achieved.

(c) Staking - Directions and amounts of movement of migrating features such as bars were documented by staking and measuring. The processes which had been inferred from morphologies were confirmed in some cases by this direct measurement.

(d) Trenching and Boxcoring - Internal structures in the sand flats were investigated by digging trenches in selected locations. Where surface features were present, they were trenched to relate the surface expression to the resulting stratification.

In water up to 75 cm deep, box cores were employed to examine the stratification. Different bedforms were boxcored to determine the stratification which resulted from their presence.

(e) Bedform Measurement - The amplitude and wavelengths of many bedforms were measured in an attempt to determine what types of bedforms were present, and the dimensional characteristics of each type. This was accomplished directly with a tape measure where the bedforms were exposed or in very shallow water. In deep water, a Raytheon DE 719 B depth sounder was employed. This instrument was capable of detecting bedforms as small as 6 cm in amplitude.

(f) Bedform Dynamics - The dynamics of the bedforms in the system were investigated by measurement of depth vs. velocity profiles over clearly active bedforms. The current meter used was a Price-type AA meter. This was held in the flow on a graduated rod, mostly from an anchored boat.

(g) Air Photos - In addition to everyday uses such as navigation and location recording, air photos were used to investigate the history of the system. Different sets of photos, ranging in time from 1954 to 1973 were compared to trace the development of the system to its present configuration.

(h) Compilation of Government Data - Large amounts of data have been collected from this river by the Department of the Environment of the Government of Canada, and the Ministry of Natural Resources of the Province of Saskatchewan. They have collected discharge data, suspended sediment data, and topographic data. Much of this has been published (Water Survey of Canada, 1965-1975), but some is available only from the agencies themselves. The Government discharge data has been supplemented by the installation by the author in the study reach of a continuous recording Stevens type A float recorder. This monitors short-term fluctuations not recorded elsewhere.

Since 1963, a programme of surveying across the river at selected locations has been carried out by the Federal and Provincial agencies. The profiles measured in different years at one locality can be compared to determine whether the reach is aggrading or degrading. By compiling the data from several locations, it is possible to determine the overall regime for a given reach over a 10-year period. This has been done for the study reach.

The knowledge or insight gained from each of these methods of research has been combined to attempt to fulfill the specific objectives of the study.

THE MAJOR RESULTS OF THE THESIS

1. In the South Saskatchewan River, the sandy bed is moulded into ripples, sand waves, dunes and bars. Dunes predominate in the deeper channels, with ripples and sand waves in the higher parts. Bars occur in both areas.
2. The river has many large braid bars or sand flats developed within it, along with channels averaging 3 m deep. Where these channels curve around an area which is dominantly sand flats, an oblique cross-channel bar is formed.
3. New sand flats form on these bars. A high area on the bar acts as the nucleus, around which the remainder of the sand flat forms. The morphologies of these small sand flats depend on the relative positions of other sand flats and islands.

4. Sand flats grow by bars accreting to them, and by bars linking them together. The largest sand flats are very old, complex features.
5. The sand flats are immobilized during the winter months because their top layer of sediment is frozen.
6. The facies sequence resulting from channel aggradation is dominantly trough crossbeds deposited by dunes. The sequence resulting from sand flat development rests on channel deposits, but is composed of planar crossbeds above these. All gradations exist between the two types.
7. Muddy vertical accretion floodplain deposits up to .5 m thick cap all the sequences.

CHAPTER II

THE SOUTH SASKATCHEWAN RIVER: THE SETTING OF THE STUDY

THE FIELD AREA

The South Saskatchewan River between Outlook and Saskatoon was chosen as the field area for the study (Fig. 1). This section of river was selected after a general reconnaissance because many large sandy braid bars are present within it. In addition, this reach also has the following advantages: 1) large amounts of Government data on the hydrology and sediments of the river are available; 2) the river is about the maximum size that could be studied with the available resources and it is large enough (up to 1 km wide) that the results of the study may be useful for the interpretation of ancient rocks; 3) roads in the area provide easy access to the river.

Within this 80 km section of river, a 10 km reach near Outlook (Fig. 1) was chosen as the primary study reach where detailed observations were to be made. This reach was chosen after surface and aerial reconnaissance showed it to be typical of the braided portion of the river.

Since 1965, the river has been controlled by the Gardiner Dam, about 25 km upstream from the study reach (Fig. 1). The presence of this dam has affected the hydrology and the sediments of the river to some extent. The results of this alteration of the natural system will be discussed later in this chapter.

GENERAL DESCRIPTION OF THE RIVER

The South Saskatchewan River near Outlook flows northward in a valley averaging 0.6 km in width, incised about 30 m into the surrounding plain. The river has an average slope of .0003. It is straight to irregularly curving through most of the field area, but within 25 km of Saskatoon, the valley widens and the river swings into a series of irregular meanders (Fig. 1 and map at the end of the thesis). The sinuosity of this reach is about 1.8. Many large meander scars and two oxbow lakes exist in the floodplain developed alongside this stretch of river.

The river system consists of the following geomorphic units: 1) vegetated floodplains; 2) vegetated islands; 3) channels; 4) very large sandy braid bars. These are illustrated in Fig. 2.

(a) Floodplains and Islands

The vegetated floodplains are poorly developed where the valley is narrow, but small areas of floodplain occur in many places the whole length of the river. The islands are very similar to the floodplains; some islands, in fact, result from the dissection of these.

FIG. 1. Map showing the location of the field area in central Saskatchewan. In the inset, Saskatoon is marked with an S. The position of Saskatoon is 52°7'N, 106°40'W. The study reach is the location of the intensive work.

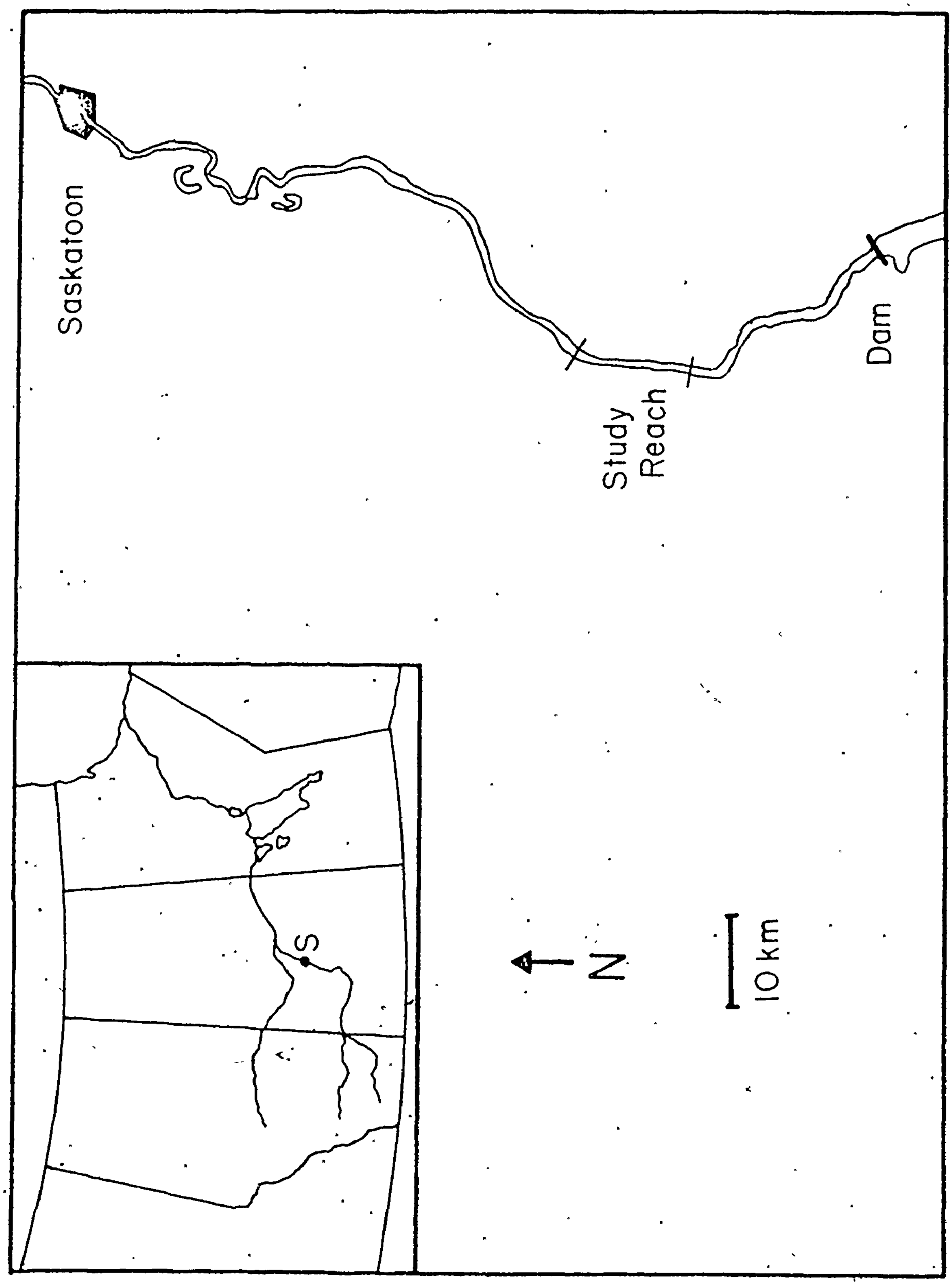

Saskatoon
Study Reach
Dam
N
10 km
S

FIG. 2. An oblique air photo in which a floodplain (bottom), a vegetated island (centre), channels and sand flats (top) are shown. Flow is to the left. The island is also shown in Fig. 38.

The tops of islands and floodplains are covered by grasses, willow bushes and, in some cases, large trees. Both these types of major elements in the river stand about 1 to 2 m above the level of the sandy braid bars. Eroded banks of both islands and floodplains show alluvial sand overlain by as much as 1 m of mud and silt. These fine-grained sediments were laid down as vertical accretion deposits (Appendix 2). In a few localities, aeolian dunes are present on floodplains and islands.

(b) Channels

The active river tract commonly has one or two major channels and several minor channels at one locality. The major channels range in depth up to 5 m below the level of adjacent braid bars and may be up to 150 m wide. Several of these are shown in Fig. 3, a typical topographic cross-profile of the river. The major channels generally flow in a direction close to the valley slope, but curve in places, crossing the river system diagonally. By making random measurements of the directions of major channels on air photos, it has been established that the average deviation from the downvalley direction is 13°, and that 90% of the measured channel directions are encompassed by a 60° wide zone. The directions of minor channels (those which cut across braid bars) show considerably more dispersion, but are of secondary importance because they rarely exceed 1.25 m in depth.

The channels are floored by a variety of migratory bedforms which will be discussed in detail in Chapter IV. Also in the channels, many transverse (foreset-type) bars similar to those reported by Smith (1971) are present. These range in height from a few cm to 3 m, and in many cases span the whole widths of the channels. To avoid confusion between these and the large braid bars, the latter will be termed sand flats.

(c) Sand Flats

The sand flats are large complex depositional structures which range in length from 50 m to 2 km (Fig. 2). Their shapes are highly variable, but all are elongated parallel to the river to some extent. The sand flats are covered by small migratory bedforms (Fig. 4), or after a high stage, by large transverse bars, but become dried out and wind eroded after several months of exposure. Sand flats are complexes of smaller features, and are comparable in scale and in importance to the point bars of meandering streams. They can be regarded as resulting from the geomorphic regime of the river and are relatively insensitive to short term hydrodynamic variations. They will be discussed in detail in Chapter VI.

(d) Sediment Type, Texture and Mineralogy

The sediment in the river is dominantly medium or fine sand with an average diameter of 0.3 mm. Although no intensive investigation of the textures of the sediments has been made,

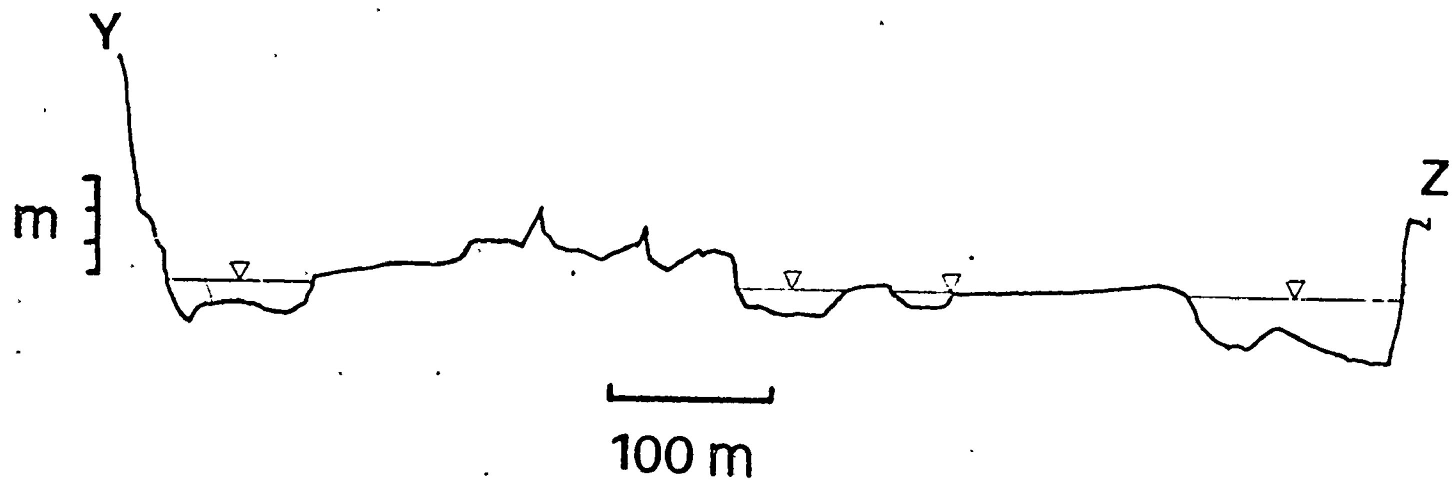


FIG. 3. A cross-profile of the river done in 1970. The location of the section is marked on Fig. 13(a). Between the time of the survey and the air photo (1971), some changes had occurred. However, the island, sand flats and major channel are all identifiable.

FIG. 4. A typical assemblage of bedforms on the top of a sand flat. These are sand waves and ripples (Chapter IV). Flow is towards the camera.

a number of samples were collected and analyzed by sieving. The data derived from these samples are presented in Appendix 1. The sands have a mean diameter of 1.55 phi and sorting of .88 (Folk and Ward statistics), i.e., moderately well sorted. Individual samples range from poorly sorted to well sorted, depending on the local environment from which they were taken. Some silts and muds exist in the system, deposited in quiet areas in the lees of sand flats, or as vertical accretion deposits on floodplains and islands. In a few places where the river cuts into the valley wall, some very coarse sediment is present, ranging up to boulder size.

The sand is composed mainly of quartz, feldspar, hornblende and sedimentary rock fragments. Locally, concentrations of heavy minerals (magnetite and garnet) occur. No detailed study of the mineralogy has been undertaken. The mineralogy noted above seems compatible with the local Pleistocene deposits being a major sediment source. Some of the grains, particularly the sedimentary rock fragments, are supplied by the local outcrops of Bearpaw Shale (section on Geology, this chapter). Before construction of the dam, sediment was being transported from the mountains of Alberta, and this source is undoubtedly represented in the river sediments at present.

THE CLIMATE OF THE REGION

The climate of central Saskatchewan is a typical continental climate, with cold winters, warm summers and relatively little precipitation. The monthly averages of temperature and precipitation are shown in Fig. 5. Wide variations from the average values of both parameters occur, however. For example, the range of temperatures recorded is from -49° to 40°C, and the maximum precipitation recorded in one day may exceed the monthly average.

The low temperatures in the winter cause the river to freeze from November to April in most years, but periods of open water may occur during thaws. The effects of the ice cover and its breakup in the spring are discussed in detail in Chapter VII.

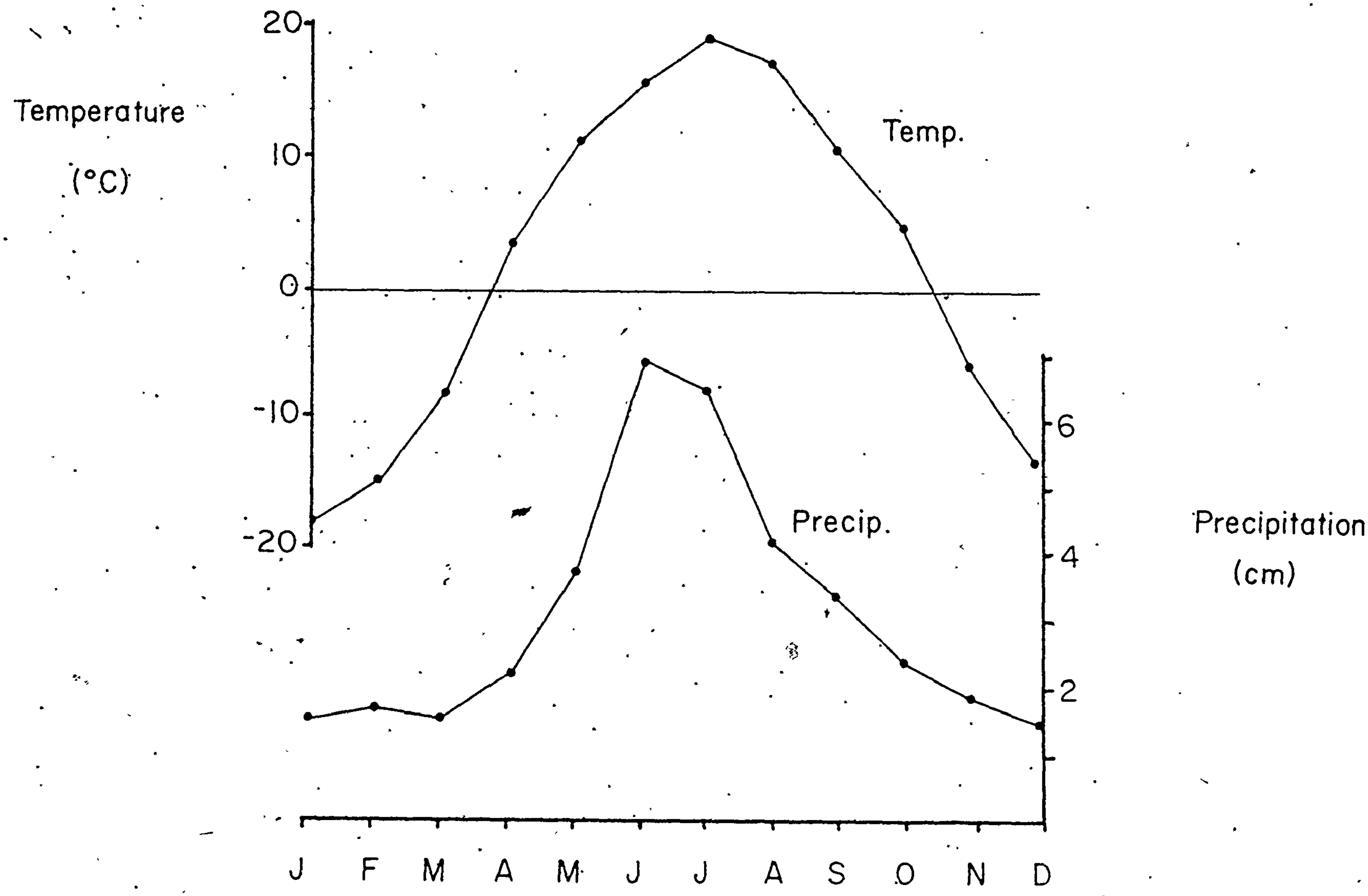
The low rates of precipitation during the winter months do not allow large amounts of snow to accumulate in the local area. Because of this, snowmelt does not provide large quantities of water most years when the temperature in the area rises above freezing and the river ice softens.

The climate of the area is one of the major external controls on the sedimentary processes in the river.

THE HYDROLOGY OF THE RIVER

Figures 6, 7, 8 and 9 summarize most of the important hydrologic data which was compiled from publications and unpublished reports of the Water Survey of Canada (1965-1975)

FIG. 5. Graphs of mean monthly temperature and precipitation for Saskatoon. (From unpublished Department of the Environment Data over 15 years.)


Temperature
(°C)
20
10
0
-10
-20
Temp.
Precip.
Precipitation
(cm)
6
4
2
J F M A M J J A S O N D

and the Saskatchewan Department of the Environment. The following data are important:

Long term (1912-1975) average discharge = 275 m^3/sec

Estimated bankfull discharge = 1270 m^3/sec

Maximum recorded discharge = 4190 m^3/sec

Figure 6 shows the wide variation in the peak flood discharge, and a smaller, but also significant variation in the yearly mean discharge, indicating that flow conditions in the river differ markedly from year to year. This fact must be considered in the development of any generalized model of river sedimentation. Several periods of higher than average discharges, both mean and maximum (e.g., 1950-1955), and others of below average discharges (e.g., 1933-1937) can be discerned in Fig. 6. These are related to climatic fluctuation. This variation in discharge may have had effects on the river, but no method exists to investigate the history of the river before the first set of available air photos (1954). Changes in river morphology due to climatic variation have been discussed by Schumm (1969), but the degree of the variations and the length of time of the variations were much greater than those shown in Fig. 6.

Figure 7 is a graph of discharge vs. recurrence interval. This shows that bankfull discharge recurs about every 2.1 years, a figure similar to those reported for many other rivers (Leopold et al, 1964).

FIG. 6. A graph of the mean (lower line) and maximum (upper line) annual discharges for 1912 - 1975. The horizontal line indicates bankfull discharge. Note the large variation in maximum discharge.

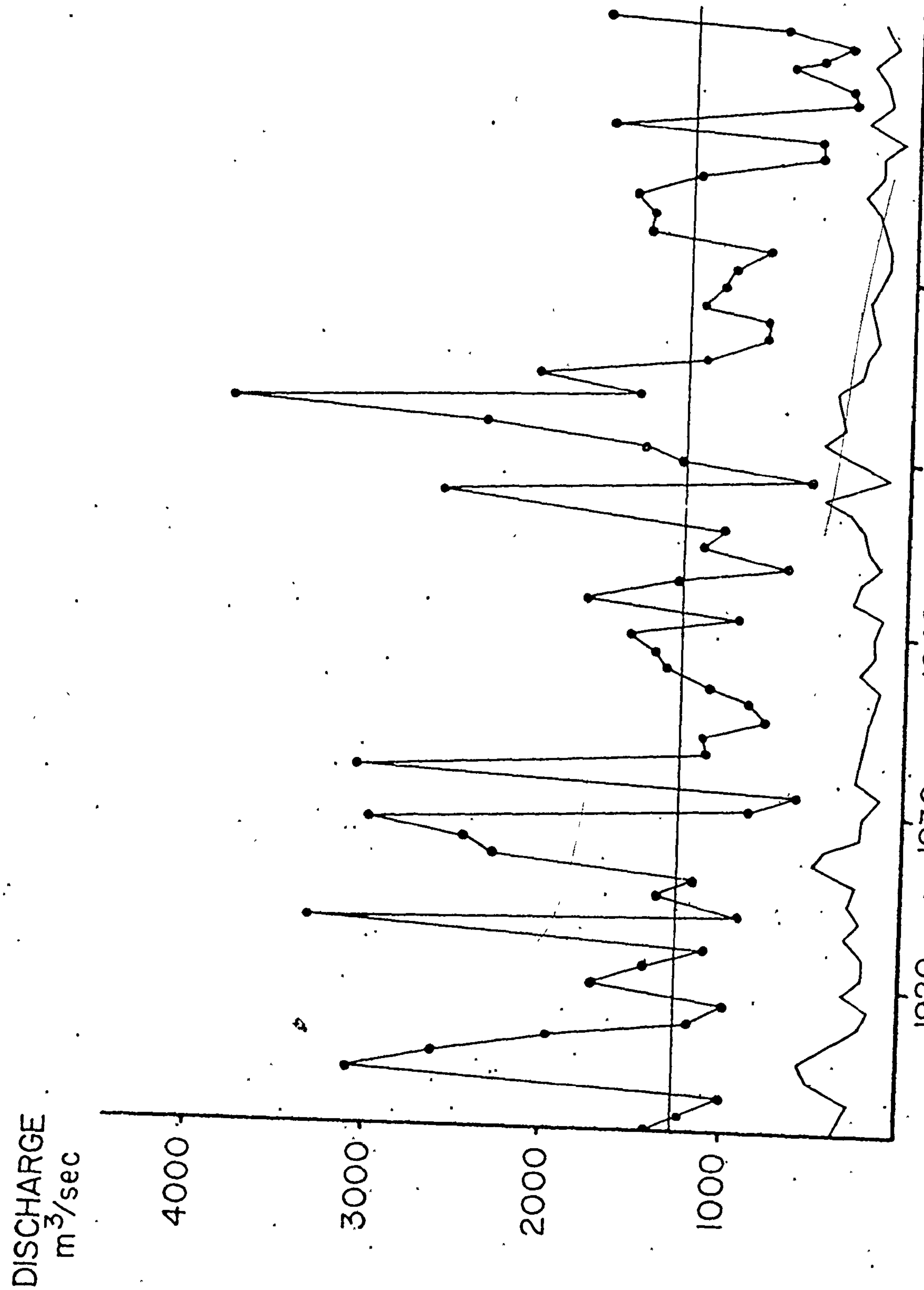

DISCHARGE
m3/sec
4000
3000
2000
1000
1920
1930
1940
1950
1960
1970

Figure 8 shows the variation in average monthly discharge throughout the year, before and after the dam was built. In the natural state, the major discharge peak occurred in June most years, but varied from late April to early July. This peak is caused by snowmelt in the mountainous headwaters of the system, and increased precipitation in the drainage basin at that time of year. The alteration of the average monthly discharges shown by the two curves will be discussed fully later in this chapter.

Figure 9 shows the discharges during the period of this study. The river was observed in all stages from very low (85 m^3/sec) to a flood stage (1812 m^3/sec) significantly above bankfull discharge. This high discharge recurs about every 4.5 years; therefore, it is a typical flood event in the river (Fig. 6). Very high flood discharges were not observed during the fieldwork, with the result that their effects on the river are unknown.

GEOLOGY OF THE AREA

Bedrock Geology

The valley of the South Saskatchewan River is cut into the Bearpaw Shale and the underlying Belly River Sandstone. The latter is a buff, fine-grained, friable sandstone of Upper Cretaceous age (Scott, 1961). It crops out on the valley wall near Outlook where large concretions are present, ranging up to 2.5 m in diameter and containing marine fossils. The

FIG. 7. A graph of discharge vs. recurrence interval (for data on Fig. 6). Bankfull discharge has a recurrence interval of 2.1 years and is indicated on the graph.

RECURRENCE INTERVAL vs DISCHARGE
(logarithmic scale)

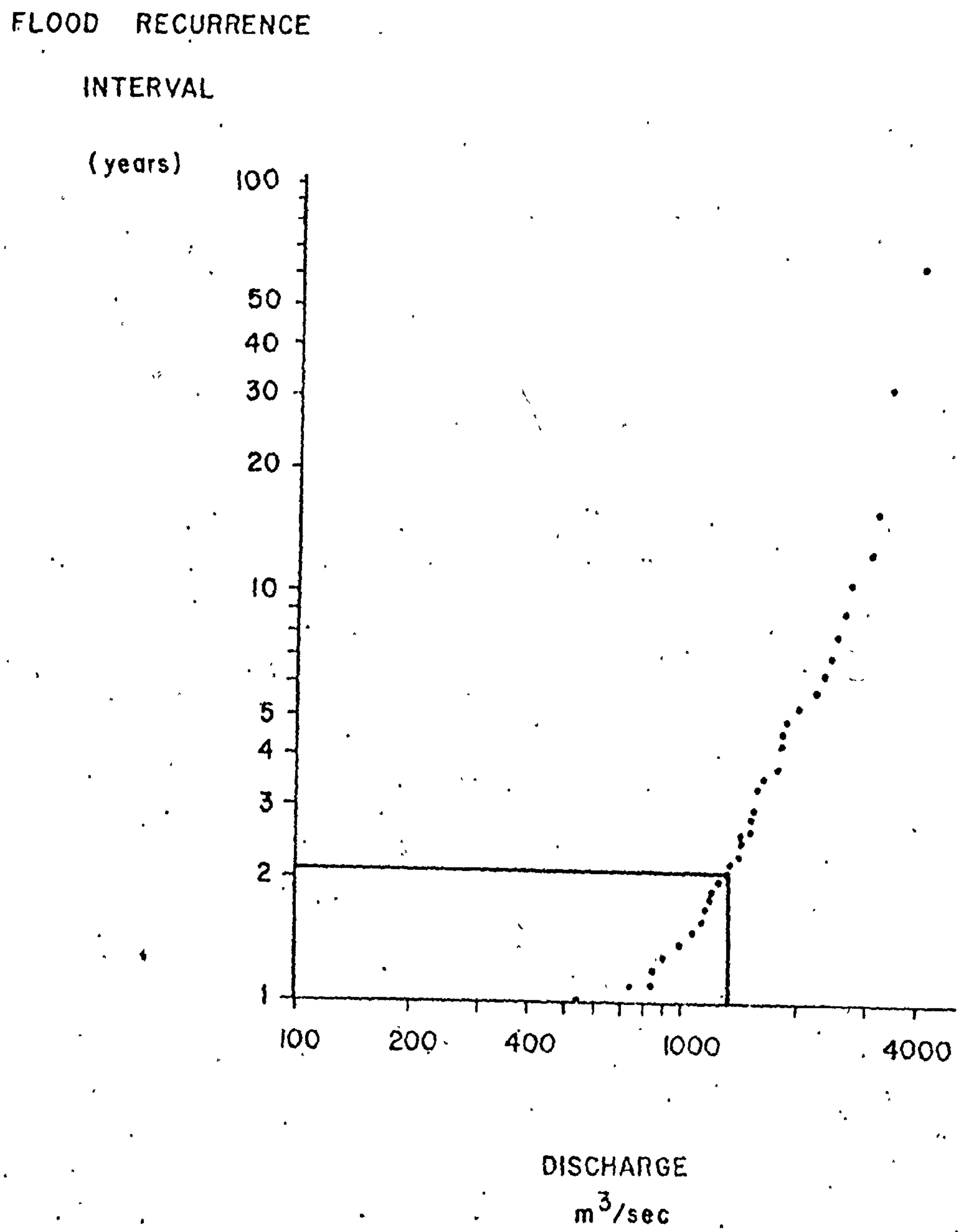


FIG. 8. Average monthly discharges before and after the dam. Note the increase in the winter months and the decrease in the summer.

The data covers the period 1912 - 1975.

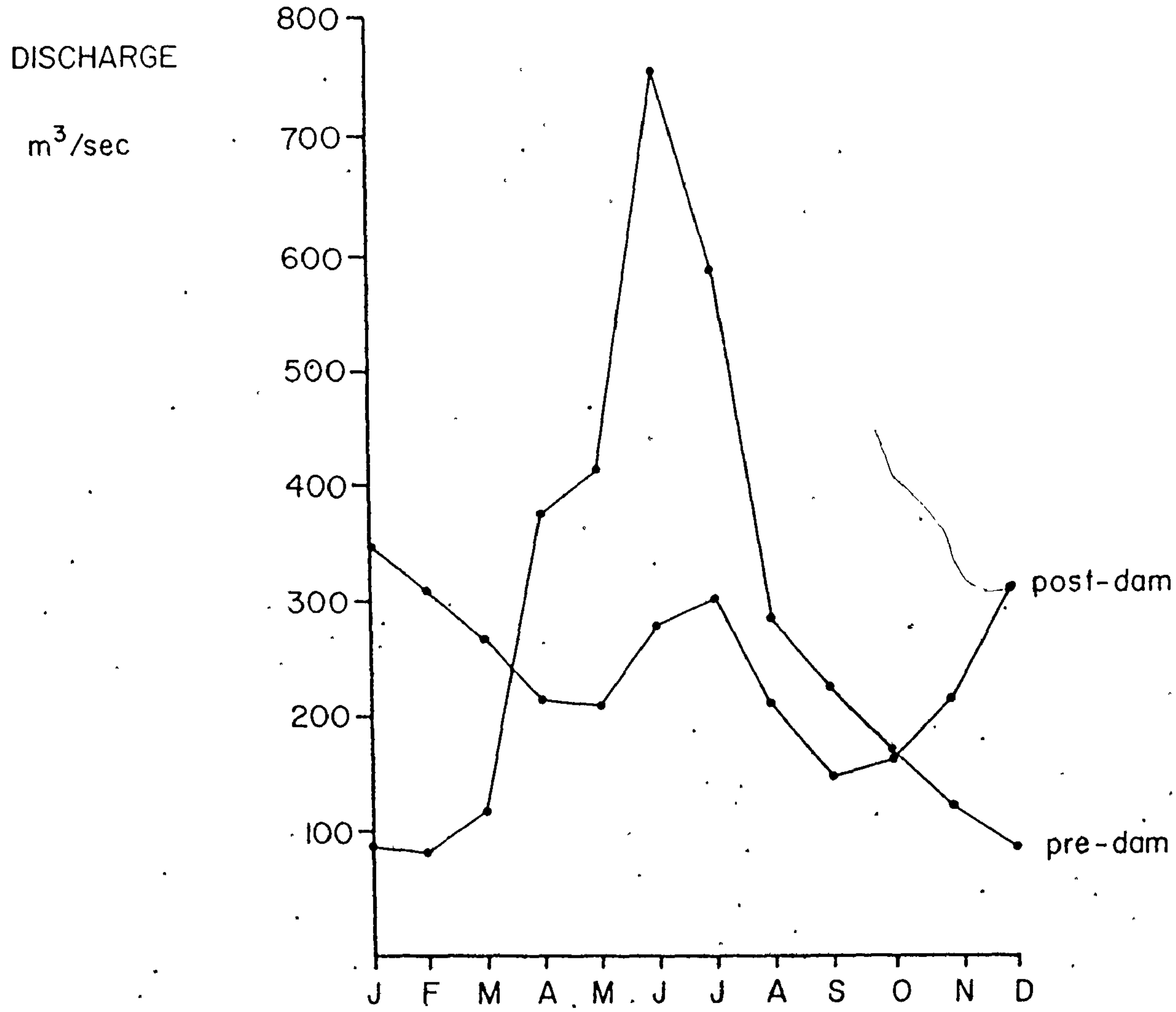
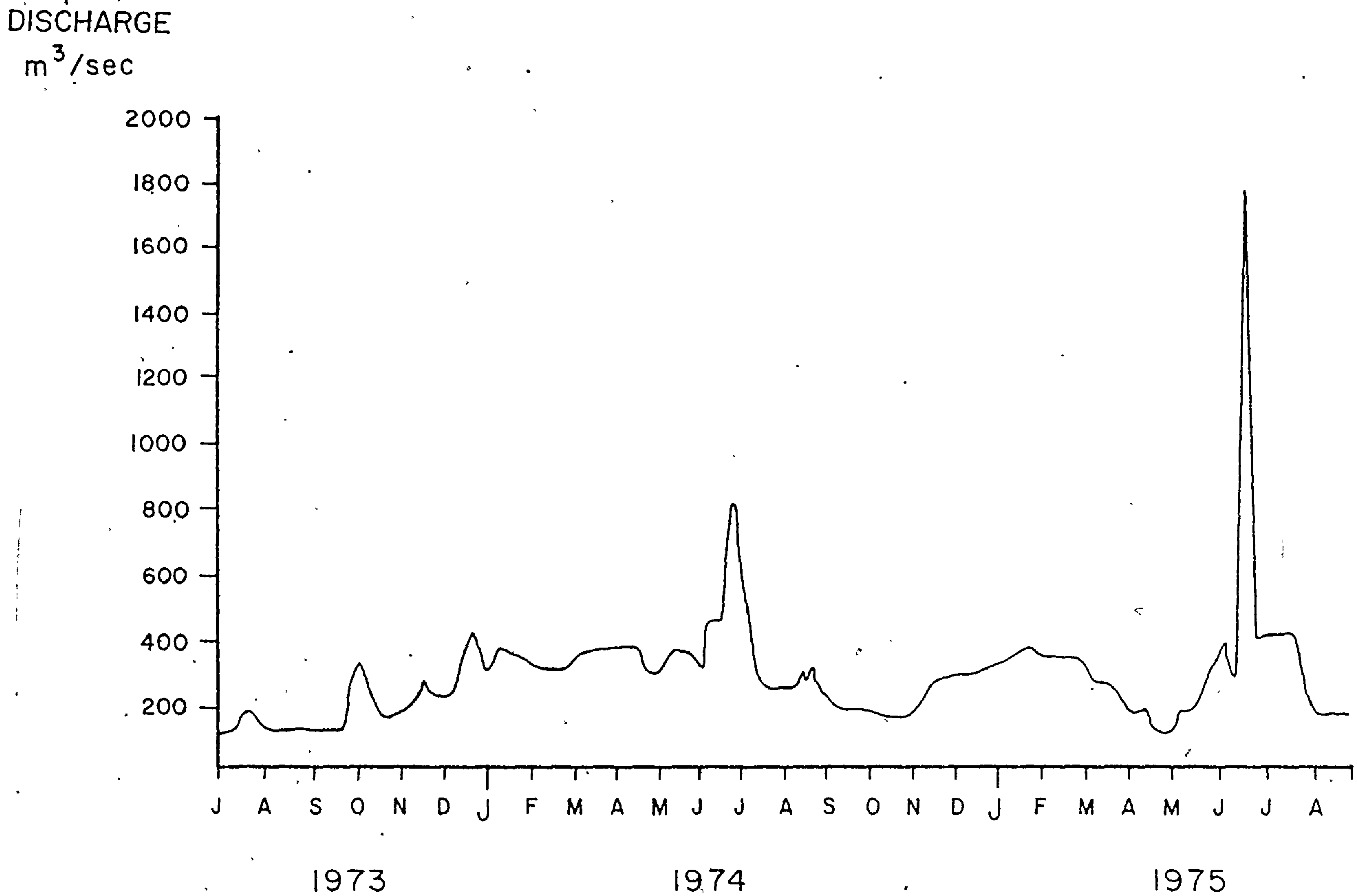

DISCHARGE
m3/sec
800
700
600
500
400
300
200
100
J
F
M
A
M
J
J
A
S
O
N
D
post-dam
pre-dam

FIG. 9. The discharges during the period of field work. Note the flood peaks in June 1974 and 1975.

The graph shows mean daily discharges. The figure on page 40 for minimum discharge refers to the lowest instantaneous discharge.

THE DISCHARGE DURING THE PERIOD OF STUDY



overlying Bearpaw Shale is a dark grey marine shale, also of Upper Cretaceous Age. Because the formation is uncemented and contains up to 80% montmorillonite, it is very soft and erodible (Pollock, 1962). It is virtually flat lying, without major structures, except along the river valley, where rotated slump blocks occur.

The bedrock geology is of significance because the two formations supply some sediment to the river, and because their soft, friable characteristics allowed the river to cut into them.

Surficial Geology

The surficial (Pleistocene and Recent deposits of the area are dominantly of three kinds: 1) sandy to gravelly tills deposited as various types of moraines; 2) lacustrine silts, clays and minor sands; 3) aeolian deposits resulting from deflation of the other types (Scott, 1961). A few major Pleistocene spillways now filled by alluvial sands and gravels are also present.

These surficial deposits are believed to supply a large proportion of the sediment in the river. A map of the distribution of the different types of these deposits in the area is given by Scott (1961). No correlation between the type of surficial deposit and any characteristic of the river in the local area has been found.

The Geologic History of the River System

In western Saskatchewan, the river follows a preglacial drainage channel, but in the study area the original valley is believed to result from erosion by meltwater flowing along a stagnant ice front (Pollock, 1962). Because flow to the north was blocked by ice, this channel drained southward through the Qu'Appelle Valley. After the ice disappeared, the river began to flow northward, deepening the valley to its maximum (about 60 m). At this time, much rotational slumping of till and shale into the valley occurred because of the increased height of the valley wall.

Since this episode of downcutting and slumping at the end of the Pleistocene, the river has been continuously depositing, aggrading about 30 m as a result. Test borings into the alluvium in the valley showed it to be mainly sand, but with some clay-rich zones and minor gravelly zones (Pollock, 1962).

HYDRAULIC GEOMETRY

The hydraulic geometry of a river system consists of the relationships between discharge and the following: 1) mean depth; 2) width; 3) area; 4) mean velocity. The way in which these parameters change with the discharge is an important characteristic of the river system which affects the sediments to a great extent. This is because the depth and velocity of the flow are important variables which control sediment properties such as bedform development and sediment discharge.

Stage-Discharge Relationship

Figure 10 shows the relationship between river discharge and the height of the water level in the study reach near Outlook. The relationship is essentially composed of two straight line segments with the break at about 230 m^3/sec. Below this discharge, the slope of the line is steeper, indicating that for a given increase in discharge, the stage rises relatively higher. The discontinuity occurs at the stage height where the sand flats become inundated. Above this discharge, the line is much flatter because of the greatly increased width of the flow.

Discontinuous rating curves for many rivers are caused by changes in friction values which occur when bedforms on the river bottom change to plane bed. It should be emphasized that the discontinuity in the rating curve for the South Saskatchewan River is not due to this factor. A second discontinuity in the curve would be expected if the bedforms in the channel changed to plane bed, but no data exist for discharges high enough to cause this.

Other Parameters

Mean depth, width, area and mean velocity of flow are shown as functions of discharge in Fig. 11. This figure is based on data supplied by the Water Survey of Canada for a cross-section a few km south of the meandering reach. This location is marked on the large scale map at the back of this

FIG. 10. A graph of stage height vs. discharge. The reason for the change in slope is discussed in the text.

Bankfull discharge (1270 m^3/sec) occurs at a stage height of about 190 cm.

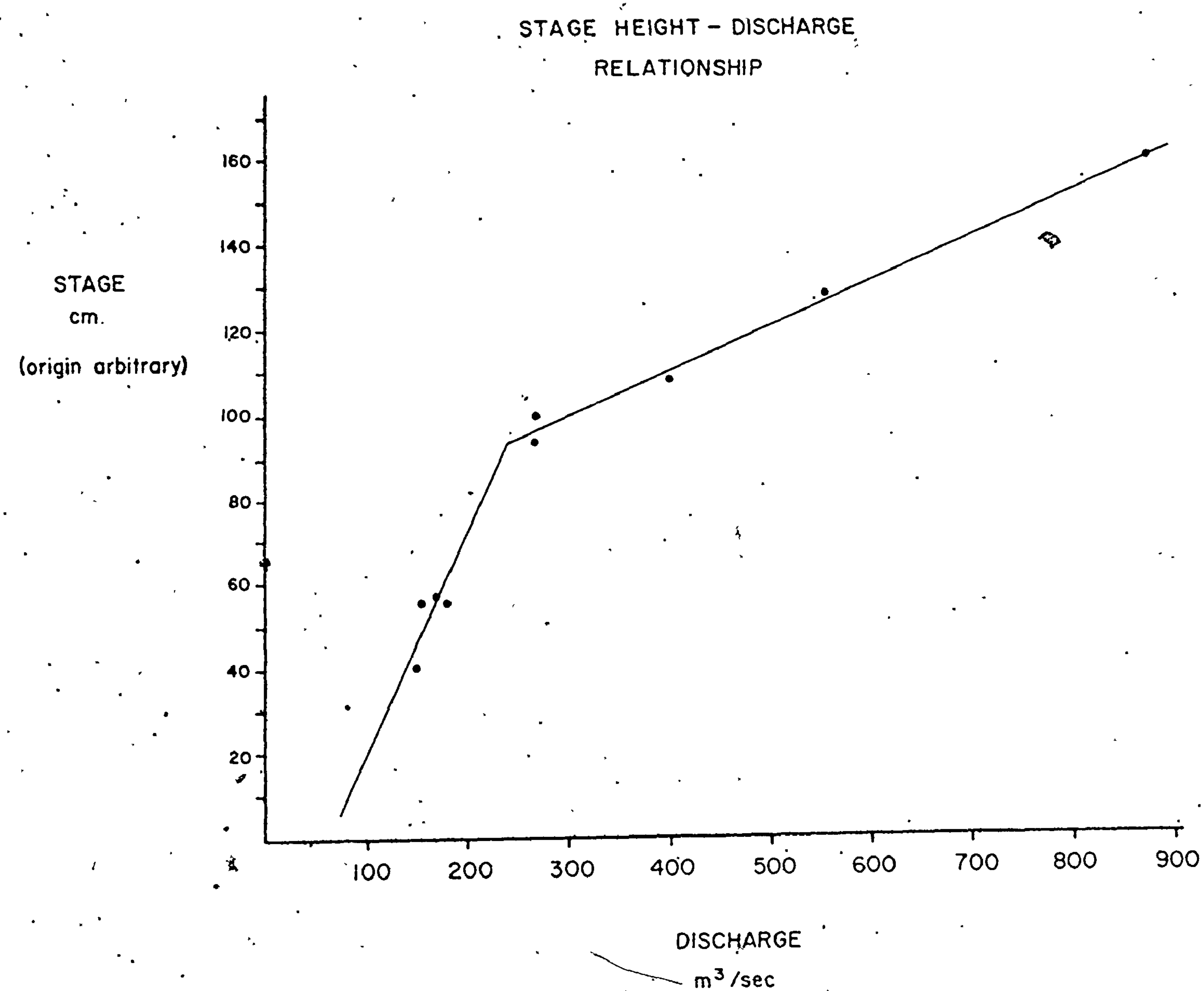
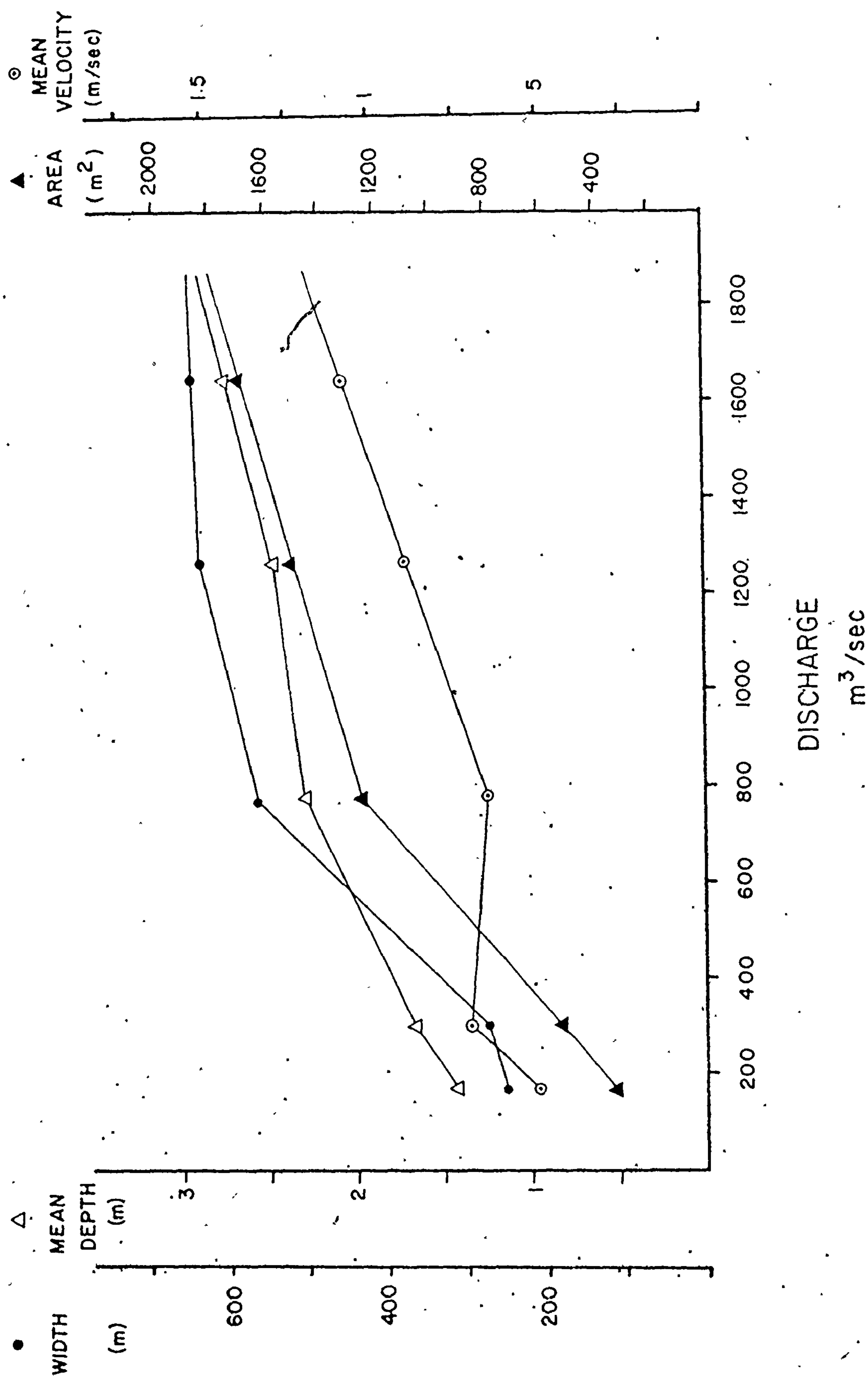

STAGE HEIGHT – DISCHARGE
RELATIONSHIP
STAGE
cm.
(origin arbitrary)
160
140
120
100
80
60
40
20
100
200
300
400
500
600
700
800
900
DISCHARGE
m³/sec

FIG. 11. The hydraulic geometry of the river. The width, depth and area of the flow increase faster than the mean velocity.
The apparent drop in velocity at 800 m^3/sec probably results from the large increase in width and area of the flow.



● WIDTH (m)
600
400
200
△ MEAN DEPTH (m)
3
2
1
▲ AREA (m2)
2000
1600
1200
800
400
⊙ MEAN VELOCITY (m/sec)
1.5
1
5
200
400
600
800
1000
1200
1400
1600
1800
DISCHARGE
m3/sec

thesis (R 51). Figure 11 shows that mean depth, width, and area of flow all increase faster than the mean velocity. Over a very large range, any increase in discharge is taken up by the area of the flow expanding, rather than by a rapid rise in mean velocity.

Although mean velocity gives no information about local high velocities in the channels, the figure serves to illustrate that very high discharges must be present before extremely high velocities occur.

THE EFFECTS OF THE DAM

The river has been controlled since 1967 by the Gardiner Dam, some 25 km upstream from the study reach (Fig. 1). Leopold et al (1964) have discussed the effects of dams on many different rivers, showing that dams change the hydrologic regimes of these rivers and cut off sediment transport, resulting in downstream degradation. In the long term, the South Saskatchewan will react in a similar manner. The question to be considered in this section of the thesis is whether the changes caused by the dam have already affected the sediments of the study reach so much that this reach can no longer be considered representative of the natural system. This question can be answered to some extent by a) consideration of hydrologic records, b) comparison of air photos taken before and after the dam, c) comparison of bed elevation profiles surveyed periodically since 1964 by the Water Survey of Canada and Saskatchewan Department of the Environment.

Hydrologic Effects

Because the main purpose of a dam is to store water, the hydrologic regime of the downstream reach is changed to a great extent. In the South Saskatchewan River, the yearly discharge pattern has been altered, with lower peak flows and much higher flows under the ice during the winter months (Fig. 8). The average discharges during the summer months are lower than they were in the pre-dam era. This results in lower sediment transport rates than would have been the case before the dam. However, because most of the major elements in the system (the larger channels, the sand flats, the islands) react only to high discharges (see Chapters V and VI), this lowering of the average sediment transport rate probably has had little impact on these large geomorphic units.

The increased discharge during the winter months under the ice (Fig. 8) affects the system because the flow is more constricted by the presence of the ice. These special effects will be discussed in detail in Chapter VII.

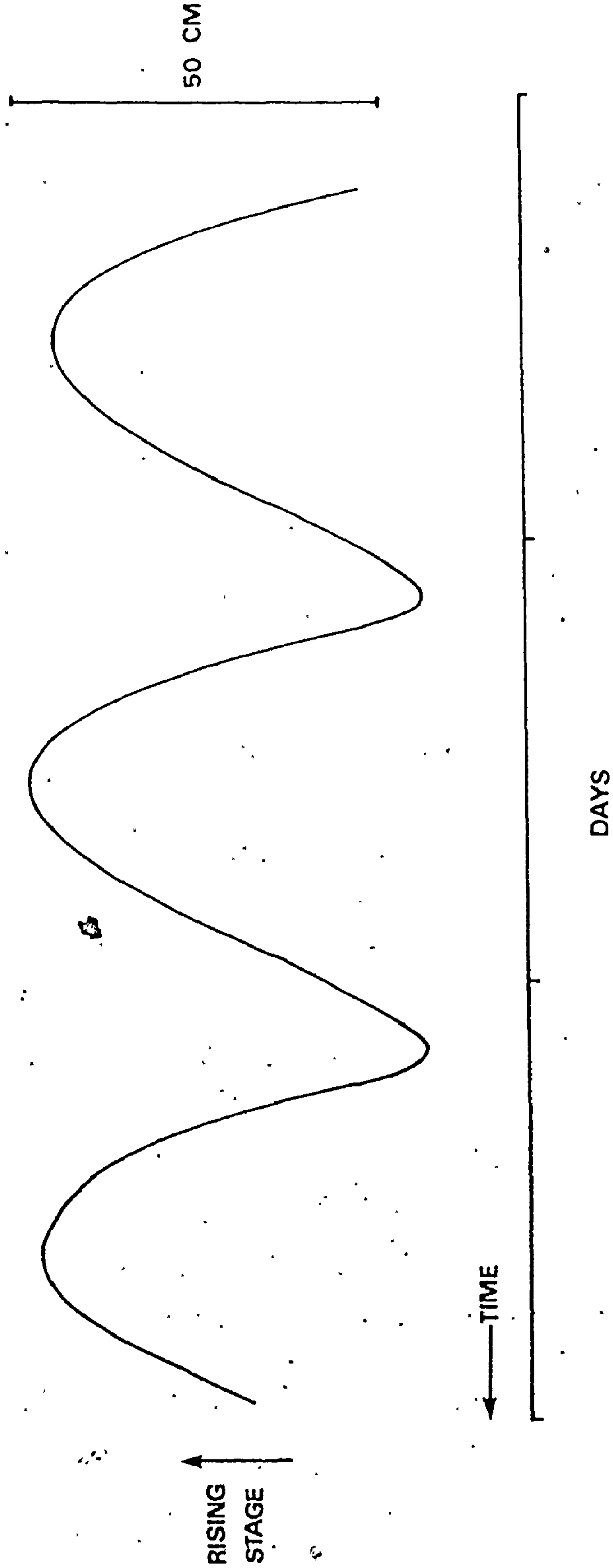
In the period 1967 - 1975, only two floods exceeded bankfull discharge (Fig. 6). This is fewer than would be expected if the dam were not present because the recurrence interval of this discharge is about 2.1 years. However, the occurrence of floods greater than bankfull in the pre-dam era (Fig. 6) was highly irregular, with periods of up to 8 years (1955 - 1963) in which none occurred.

The maximum discharge has been reduced most years by the dam. The peak discharge during the 1975 flood (1812 m^3/sec) was reduced from 2800 m^3/sec which flowed into the reservoir.

This reduction in number and maximum size of flood peaks has reduced the transporting capacity of the river to some extent. The 1975 flood, however, was greater than the mean annual flood of 1450 m^3/sec, so it can be considered representative of flood events in the river.

Changing demand for power generation throughout the day has resulted in discharges being varied on a daily basis. This fluctuation is superimposed on the longer term variation. This is illustrated by Fig. 12, a stage recorder record made in the study reach. This daily fluctuation in stage height occurs only at low discharges (less than about 230 m^3/sec) when the sand flats are exposed. At higher discharges, presumably, enough power is generated at all times to meet peak demand. Because the variation is limited to low stages, it has little effect on the major structures of the river, but has many minor results. Some of these are: 1) falling water marks are common on bar fronts; 2) runoff ripples are present in the troughs of higher stage bedforms; 3) sediment transport is intermittent down some minor channels; 4) in some cases, the bedform type is indeterminate due to superimposed and non-equilibrium forms.

FIG. 12. A tracing of the stage recorder record during the period 7:30 p.m. August 8 to 7:00 p.m. August 11, 1975. The mean discharge is 122 m^3/sec.


50 CM
DAYS
TIME
RISING STAGE

Comparison of Air Photos

Two air photos, one taken in 1967 and one in 1971, showing the same reach, are presented in Fig. 13. From these, it can be seen that some shifting in the positions of channels and sand flats has occurred. However, little change can be seen in the type and relative abundance of the major elements in the system. Examples of each of these major structures are labelled on the photos for direct comparison.

Figure 14 is an air photo of the river taken in July, 1959, when the river was much higher than in Figures 13a or 13b. In this older photo, one of the major differences which is apparent is the turbid nature of the water. The suspended sediment concentration was lowered by 4/5 by the creation of the reservoir. Before the dam, at bankfull flow, the suspended sediment concentration was about 1.5 gm/litre. After the construction of the dam, the concentration was .3 gm/litre for the same discharge (Water Survey of Canada, 1965-1975). The major elements in the river, however, are very similar to those identified in Fig. 13. They are again labelled by numbers.

Government Profile Data

Since 1964, selected profiles across the river have been repeatedly surveyed at irregular time intervals by the Federal and Provincial Government agencies. They have issued periodic project reports which include the data obtained from

FIG. 13. Two air photos of the same reach. Photo (a) taken in 1971 and photo (b) in 1967, with the discharges 86 and 47 m^3/sec respectively. Shifting of channels has occurred, but some similarity in pattern is present. Y - Z shows the location of the cross-profile in Fig. 3. The numbers are referred to in Fig. 14. (Photo (a) is 154.)

(a)

(b)

FIG. 14. An older air photo taken in 1959. The stage is higher than in Fig. 13 and the water is extremely turbid. The numbers refer to (1) sand flat, (2) cross-channel bar, (3) vegetated island, (4) channel, (5) new sand flat nucleus, (6) large bedforms. These can be compared with the features numbered the same on 1971 photos in Fig. 13(a), 38(a).

these surveys (Water Resources Branch, Department of the Environment and Saskatchewan Department of the Environment, 1969 - 1973). These profiles have been analyzed in an attempt to determine whether these reaches have aggraded or degraded. Two different methods have been used to do this: 1) comparison of elevations of the beds of major channels; 2) comparison of total amounts of sediment at a cross-section.

1) Channel Bed Elevations - Reconnaissance of the river immediately downstream of the dam showed that it appeared to be downcutting. The major channel was incised and eroding laterally into sand flats. The degradation, therefore, was not occurring uniformly over the entire width of the river, but was proceeding by incision of the major channel. It is believed, therefore, that comparisons of the minimum elevations of profiles made at the same location but in different years will detect any degradation which has taken place. All the raw data for this comparison are given in Table 2. Each range (survey site) is identified by a number which is the distance in miles measured downriver between it and the dam. Because the Government agencies involved are using these mileages to designate the ranges, it was decided to leave the distance in miles in order to avoid confusion. For reference, the upstream end of the study reach is between ranges 14.7 and 17.4. The ranges are located on the map at the back of the thesis.

TABLE 2

THE ELEVATIONS OF THE BEDS OF MAJOR CHANNELS (in metres above sea level)

Range	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
1.0				497.8	497.4	497.8	497.0	496.6	496.3	496.4
2.7	498.1			497.7	497.5	497.0			496.7	
5.0	496.5	494.8	496.6	495.2	495.6	496.1	495.7	496.2	496.6	496.6
7.5		493.9		493.6		493.2		494.1		
8.0	495.3	495.4	495.2	495.3	495.3		495.3	495.1	494.9	494.5
10.0	494.7	493.9				493.2		493.8		
12.0	493.2	493.5		494.2	492.7	493.3				493.4
14.7	492.3	491.5	492.1			491.1	491.7			
17.4		491.0		490.9		487.1	489.6	491.0	491.0	491.0
21.0	489.2	489.6	487.9			489.3	489.9			
26.0	487.8	488.2	488.4			488.6	487.6			
30.2		485.4		486.1		486.7		486.8		
33.0	485.6	485.5	485.3			485.1		485.4		
36.0	483.9	483.3	483.8			484.4	483.8			
41.0			481.8			482.4	481.9			
43.8		481.7				481.2			481.4	
47.0	487.9	479.2	479.8	479.7		480.3	479.3	483.7	479.5	479.7
51.0	476.4	477.0				477.2				477.0
54.0	477.4	475.6	476.5			476.6	476.0			
55.5		476.9				476.6				
59.1		473.2								474.7
62.2	474.1	473.3	474.3			474.6		474.6		
63.3	472.5	472.8				473.8				473.4
64.5		472.6				471.1				473.2
70.0	471.1	471.6	471.1		472.1	471.2				
71.5	471.4	470.4	471.2	471.2		471.4	469.6	471.4	471.6	471.7

Inspection of Table 2 reveals that the bed elevations in most ranges are highly variable from year to year, presumably as a result of shifting channels and bars. However, the data from ranges 1.0, 2.7, and possibly 8.0 show trends indicating incision of the channel.

The ranges in the study reach (17.4, 21.0) show no clear trend towards downcutting. This is a good indication that the presence of the dam had not caused major amounts of incision at the time of the study.

2) Total Amounts of Sediment - The total amount of sediment at a cross-section was obtained by measuring the area on a profile above an arbitrary datum. This was done by planimeter which was accurate to about 15 m^2. By using the same arbitrary datum, the change in the total amount of sediment between successive profiles was obtained.

This method was applied to profiles crossing the intensive study reach. The raw data is presented in Table 3. The net changes in all cases are less than the variations recorded over the single year intervals. Inspection of the profiles reveals that the changes are due, in most cases, to lateral bar growth or erosion, with little consistent change across the entire width of the profile.

TABLE 3

CHANGES IN TOTAL AREA BELOW SUCCESSIVE PROFILES

REACH 17.4

Year	Change in area from previous survey (m^2)
1965	---
1967	-431
1969	+349
1970	+149
1971	- 52
1972	+ 52
1973	- 45

Net change 1965 - 1973 = + 22 m^2

REACH 21.0

1964	---
1965	+164
1966	- 45
1969	- 8
1970	-134

Net change 1964 - 1970 = - 23 m^2

REACH 26.0

1965	-222
1966	-290
1969	+691
1970	

Net change = + 179 m^2

Accuracy estimated to be ± 15 m^2

This conclusion regarding the lack of major amounts of degradation in the study area contradicts a Government report (Saskatchewan-Nelson Basin Board, 1972), which predicted rapid degradation in the field area. However, this prediction is based on regime theory, an empirical set of equations developed for meandering canals in the Indian subcontinent (Blench, 1963). It is doubtful whether these equations may be applied with any degree of certainty to a braided river. The report cited above actually denies the presence of braided rivers in the Saskatchewan River basin.

In another section of that report, a sediment discharge rating curve for the study reach is given. This curve is based on the theory of bedload discharge (Einstein, 1942; Colby, 1964), rather than actual measurement. Therefore, the accuracy of the curve is somewhat questionable because of the difficulty of applying the theoretical concepts to a complex braided river. However, by using the rating curve and the recorded discharges, the total sediment discharge between the closing of the dam and the initiation of this study can be calculated. This is found to be about 3×10^6 m^3 of sediment (assuming 30% porosity).

From this, the depth of degradation may be calculated if the area undergoing degradation is known. If the downcutting takes place over the whole width of the river, the maximum degradation in the study reach would be about .1 m, and if the main channel only (100 m wide) is considered to incise, the degradation would be about .6 m. This calculation considered different total lengths of degradation, but with the volume fixed.

The actual amount of degradation probably lies between these extremes. Winter conditions may cause the main channel to incise (see Chapter VII), but discharges greater than 250 m^3/sec cause sediment transport on the sand flats, and allow redistribution of sand from the flats to the channels.

This depth of degradation probably has had little effect on the major elements in the system because they are larger than the .1 to .6 m estimate.

The Effects of the Dam: Conclusions

The dam has markedly affected the discharge regime by reducing the number and size of high flood stages, thus reducing the sediment transporting capacity of the river. In spite of this, a typical flood event which closely approached those of the pre-dam era occurred during the period of the study.

The increased discharge during the winter months is constricted by the ice cover. This may cause erosion of the channel bed. This special effect will be considered fully in Chapter VII.

The daily stage fluctuations have no important effects on the system because they occur only at low flows.

Consideration of different sets of air photos show that the types of the major elements in the system have not changed since the dam was built. A reduction in the amount of suspended sediment is evident, but this would have little effect on the major elements of the system.

The cross-profiles of the river show that while the major channel near the dam is incising, this has not yet affected to any great extent the area where this study was made. Variations in the amount of sediment at a particular location are due more to channel and bar shifting than to degradation.

The presence of the dam has had some effects which benefitted this study. The reduction in the amount of suspended sediment allowed direct observation of channel beds and the bedforms on these at most stages. The very low discharges in late summer caused by the dam allowed deeper trenching and box coring than would have otherwise been possible.

It can be concluded that the dam has not had enough effects on the study reach to render it very different from the natural case.

CHAPTER III

THE LARGE SCALE GEOMORPHIC ELEMENTS AND THEIR ORGANIZATION

INTRODUCTION

In meandering rivers, there exists a clear quantifiable organization of channels and point bars. This organization has been described in terms of a series of non-linear empirical equations relating meander length, amplitude, radius of curvature and channel width (Leopold et al, 1964). Schumm (1969) has shown that the type of sediment load, particularly the amount of silt and clay, affects these relationships.

In braided rivers, however, no organization of this type has been recognized previously. In this chapter, the South Saskatchewan River will be considered on a large scale so that the major geomorphic elements and their organization may be understood. The map of the river at the back of the thesis illustrates this scale.

The organization of the river system reported in this chapter provides the basis for understanding the context of the individual elements discussed in later chapters and how these elements relate to one another. These relationships are presented diagrammatically in the form of a conceptual framework for the river system.

THE LARGE SCALE GEOMORPHIC ELEMENTS

(a) Sand Flat Complexes

Many areas exist in the river where extensive sand bodies have accumulated. In some cases, these areas consist of one very large sand flat, but in other cases they are composed of more than one sand flat with intervening minor channels (Fig. 15). The minor channels are shallow, not exceeding 1.25 m in depth below the level of the nearby sand flats. The largest of these depositional areas, termed sand flat complexes, range in length up to 5 km.

The map at the back of the thesis shows the locations of these sand flat complexes in the river. This map shows that they do not occur with any pattern or regularity. Some are attached to the banks, whereas others are present in the middle of the river. No consistency in the size or spacing of these complexes has been detected.

(b) Major Channels

At any locality in the river, only one or two major channels are present. These channels flow around, beside and between the sand flat complexes. They wander irregularly through the river system with no apparent pattern. (See map at back of thesis.) Although the major channels cross from one bank to the other in many places, they do not appear to be meandering within the system. They may have sand flats and bars developed within them, but only in localized areas.

(c) Cross-Channel Bars and Bar Systems

Any slipface-bounded, delta-like (Jopling, 1965) wedge of sediment in the river is generally termed a bar in this thesis (see Chapter IV). However, some bars extend diagonally across the entire widths of major channels, linking sand flat complexes, islands and river banks. The slipfaces of these diagonal bars are at high angles to the local river direction, deviating an average of 69° from this. The bar fronts may be up to 2.5 m high. They are extremely important geomorphic elements in the river system, and are here termed cross-channel bars.

In many places, the flow over a large cross-channel bar is divided by one or more sand flats developed on the top of the bar (Fig. 16). In many cases, the sand flats formed after the cross-channel bar, but in others the bar incorporated pre-existing sand flats into itself. This more complex form is termed a bar system. The major bar systems and cross-channel bars are marked on the map at the back of the thesis.

(d) Vegetated Islands and Floodplains

The vegetated islands occur throughout the river system without any detectable patterns of size or location. This randomness occurs because of the modes of origin of the islands. Some are erosional remnants of floodplains which have been dissected by major channels. Others apparently result from the stabilizing action of vegetation on aeolian and sand flat

FIG. 15. A large sand flat complex with many minor channels within it. The major channel flows around it. The letter 'L' denotes linguoid bars. (Photo 145)

FIG. 16. An oblique air photo of a large bar system which extends from the sand flat in the foreground to the bank in the background. Several sand flats are present as part of the bar system. A small sand flat nucleus (Chapter VI) is present on the cross-channel bar. Flow is from the lower right to the upper left.


N
100 M

deposits which allowed a vertical build-up of sediment. Accumulation of fine-grained cohesive sediment on the tops of these mounds converted them into semi-permanent islands.

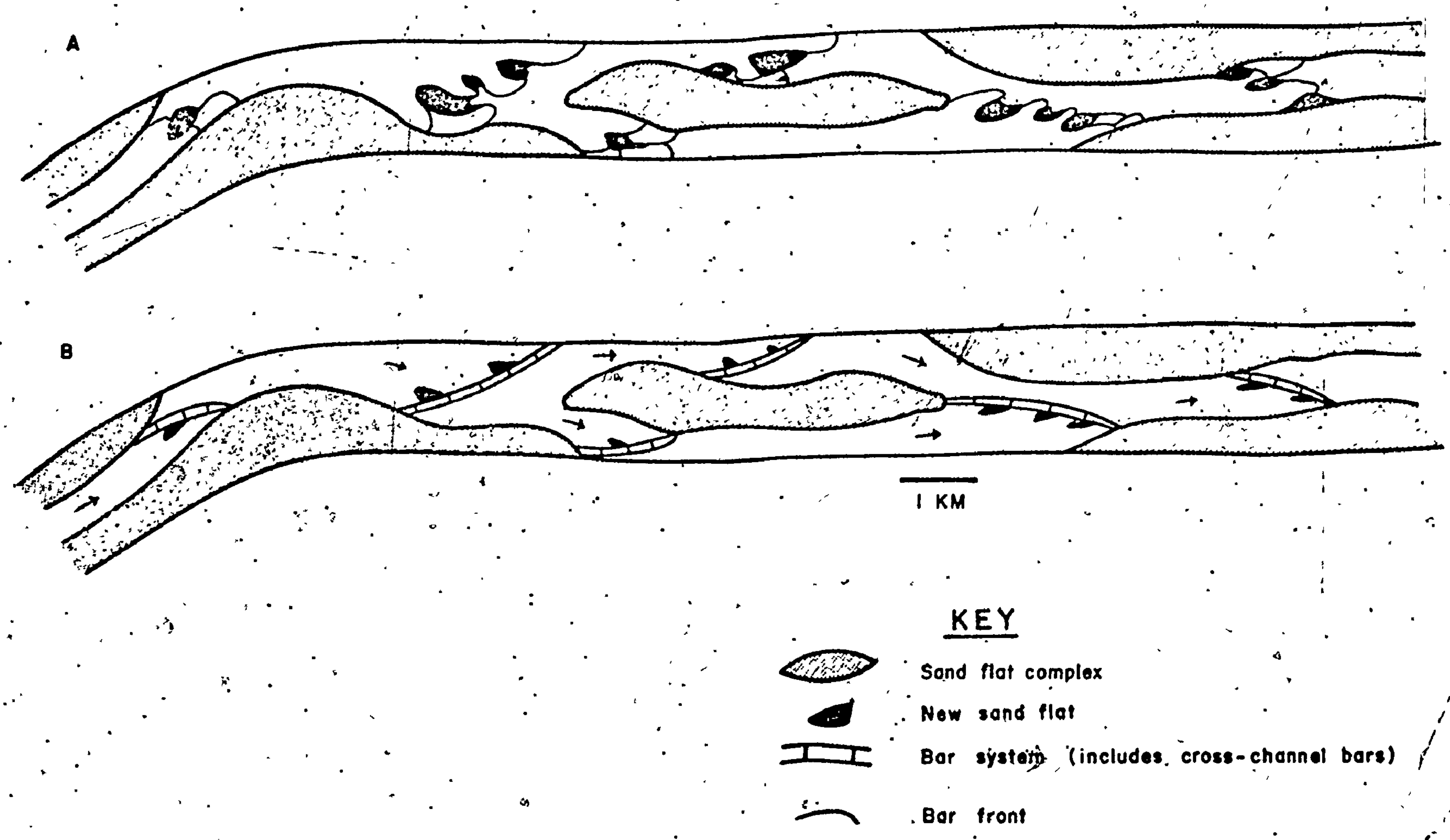
Floodplains differ from islands in that they are attached to the valley wall, outside the river channel itself. They also originate from sand flats (Appendix 2), with vertical accretion of cohesive muds. Stabilization by vegetation again plays an important role in the development of a floodplain. Areas of floodplain occur at many localities in the river. Some occupy erosional cuts in the valley wall, but others extend 100 m into the valley. In common with the islands, no regularity of size or spacing of the areas of the floodplain is present. The islands and floodplains are also on the large scale map at the back of this thesis.

THE ORGANIZATION OF THE RIVER

The organization of the river is shown on the map at the back of this thesis and is presented in more detail in Fig. 17b. Both the map and the diagram were prepared from a set of air photos taken at low river discharge after several months of low-stage modification. A typical configuration actually seen on the photos is presented in Fig. 17a. This was interpreted and simplified to give Fig. 17b and the map at the back of this thesis.

FIG. 17. Part (a) shows a hypothetical reach of the river as it appears, and part (b) shows the interpretation of the same reach.

LARGE SCALE ORGANIZATION



The active river system may be considered to consist of many large sand flat complexes, along with one or two major channels. At cross-sections where the sand flat complexes are wide, occupying much of the width of the river, the major channel is narrow and deep (see Chapter V). Where this channel bends (commonly as it flows around the downstream margin of a sand flat complex), a cross-channel bar forms oblique to the downstream direction (Fig. 17b). The reasons for bar formation are discussed in Chapter IV. On the top of this bar, the channel is wide and shallow and may split up into a series of smaller channels with small sand flats between them. The cross-channel bar could then be considered a bar system because of sand flats developed on it. The tops of these cross-channel bars are the major loci of formation of new sand flats in the river (see Chapter VI). Downstream of the bar system, the flow is constricted laterally because of the oblique nature of the bar system and the presence of other sand flats, islands and the river banks (Fig. 17b). The whole sequence is then repeated in the next reach downstream.

This pattern of the river forming bar fronts where it expands laterally has little regularity. The spacing between the bar systems is highly variable, and the directions of successive bar fronts may be the same or different. (See map at back of thesis.)

The pattern of a narrow, deep channel gradually broadening and shallowing up to a bar front is similar in some ways to a pool and riffle sequence. However, the and riffle sequences of some authors (Leopold et al, 1964) have regular spacings and are probably different in origin from the deep to shallow sequences reported here.

COMPARISON WITH THE MEANDERING REACH

The large scale map at the back of this thesis shows that the river swings into a series of irregular meanders (sinuosity 1.8) about 20 km south of Saskatoon. The abundance of meander scars and the presence of two oxbow lakes in the floodplain beside this reach show that the river has been meandering here for a relatively long period of time. The meandering reach also has sand flats developed within it (Fig. 18), so it is very different from other meandering rivers reported in the literature. A river which meanders, but is braided internally is not even considered in most river classifications (Leopold et al, 1964).

In the meandering reach, most sand flats are developed along the sides of the river. Many of these are present as point bars on the insides of meander loops. However, some major sand accumulations are present on the outsides of the bends where classic meandering theory (Leliavsky, 1966) predicts the thalweg should be. In some meanders, more sediment is present on the outside of the bend than on the next point bar downstream, with the result that the major channel is less sinuous than the river. This may represent a tendency towards straightening of the river. The meander pattern, therefore,

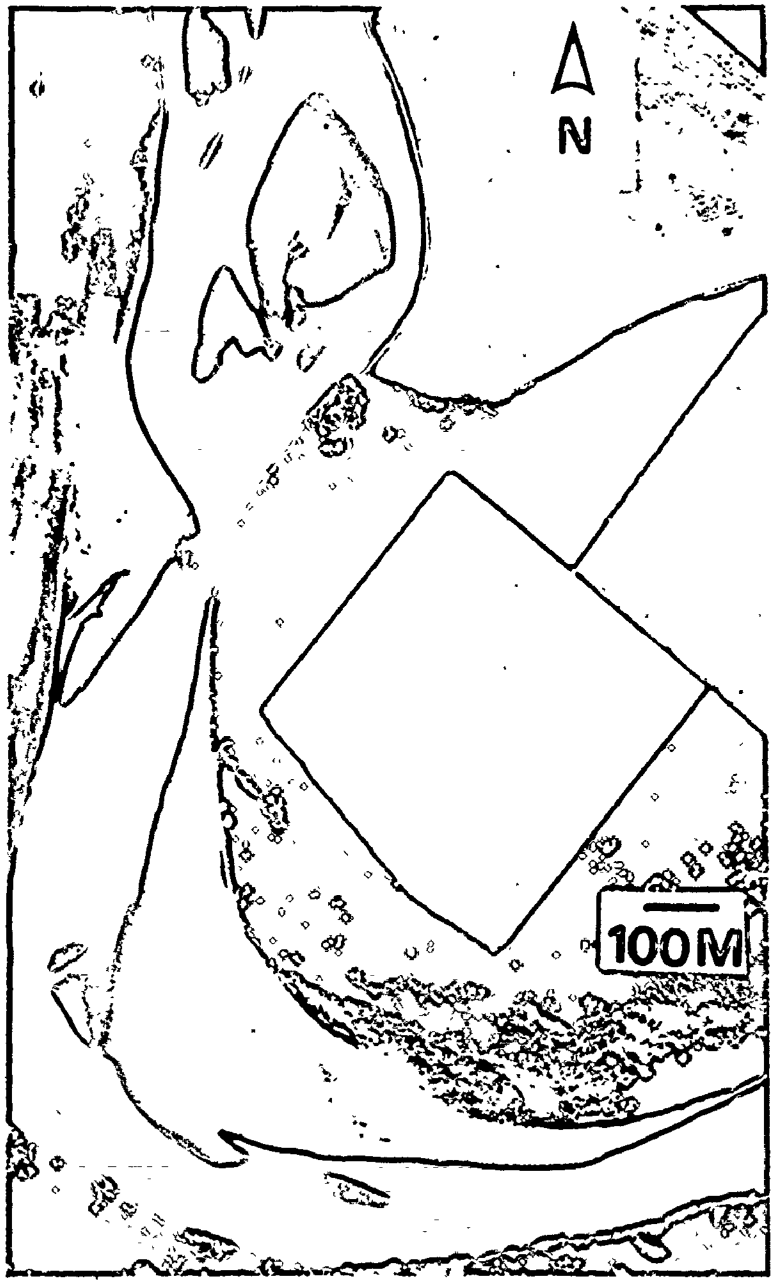


FIG. 18. A large meander bend in which sand flats are developed. Where the flow spills to the outside of the bend, a large cross-channel bar, here partly eroded, is developed. As the flow leaves the bend, another cross-channel bar is formed, facing towards the other bank. (Photo 54)

may be a relict non-equilibrium feature. Only long-term observation will be able to confirm or refute this speculation.

Whether or not the meandering is relict, it imposes an organization on the major geomorphic elements within the reach. Wherever the channel is forced to bend because of a meander, it deflects laterally towards the outside of the curve. As it does this, it forms a large cross-channel bar or bar system where it enters the bend and spills over to the outside bank (Fig. 18). As the channel leaves the bend and enters the next, it spills back in the other direction, forming another cross-channel bar which faces the opposite bank. Many of these large cross-channel bars and bar systems extend the width of the entire river tract. They link sand flats developed in the point bar position to others developed on the outer bank.

This organization of the meandering reach is similar in some ways to the organization of the braided reach. In both, major bar systems form where sand flat complexes terminate downstream, and where the flow bends laterally. In the braided reach, a curve in the river course (e.g., 5 km south of Outlook) causes the main channel to cross to the outside of the bend, forming a large bar system, similar to the pattern developed in the meandering reach. The same basic organization appears to be present in both reaches. The main difference between the two is that the meander bends impose more regularity on the locations of sand flat complexes and major bar systems.

CONCEPTUAL FRAMEWORK OF THE RIVER SYSTEM

The large scale organization of the river leads to understanding about the relationships among the bedform types (see Chapter IV), the channels, sand flats and the larger elements discussed at the beginning of this chapter.

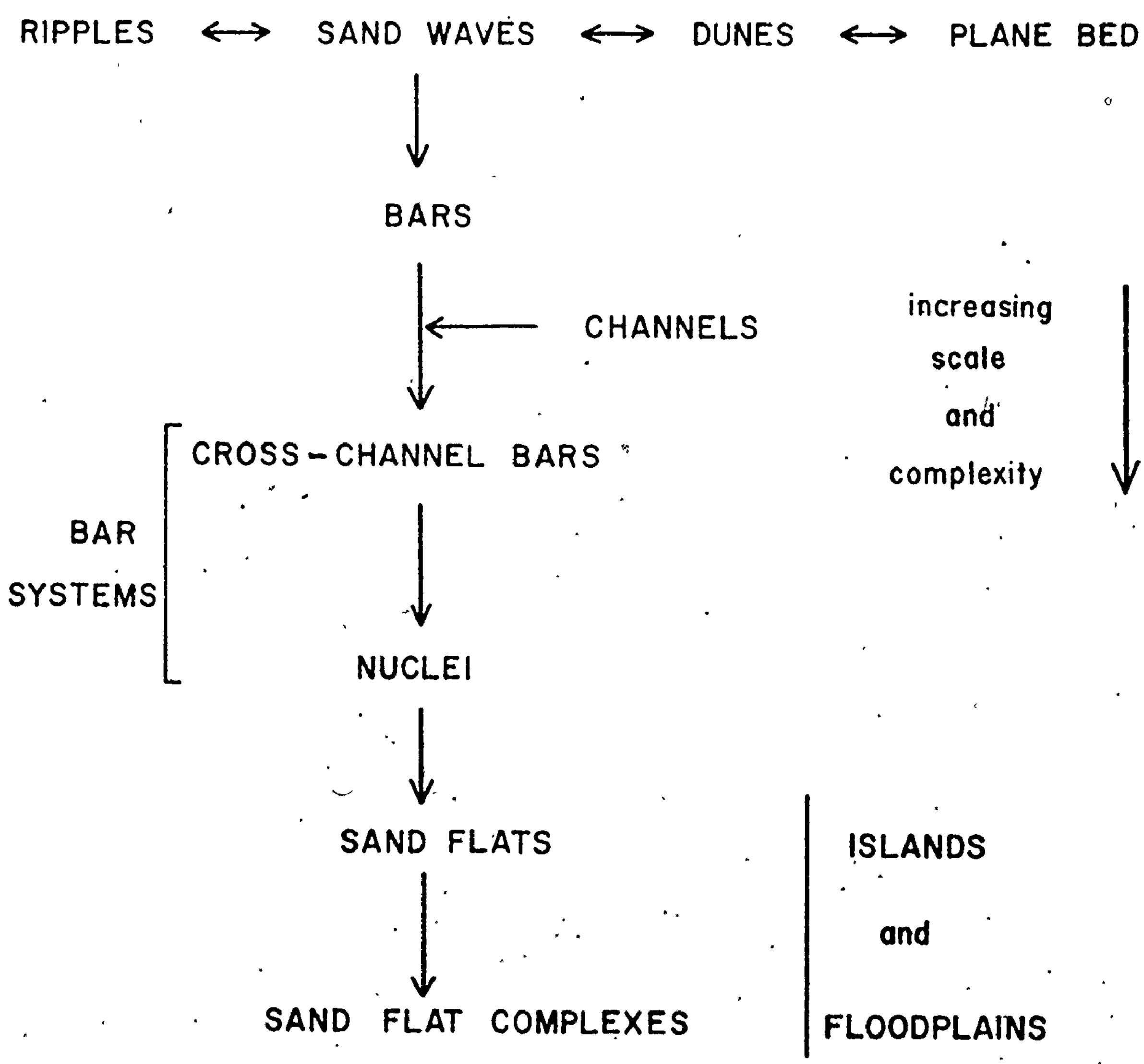
The conceptual framework developed is presented in Fig. 19. This figure illustrates relationships of type, origin and scale among the features listed above.

The top line, consisting of ripples, sand waves, dunes and plane bed, represents bedforms which can be generated in flumes, and are the first level of organization of individual grains. Sand waves may combine to form bars (see Chapter IV), and all the other bedform types may be present on their tops, contributing to their growth (Chapter IV). Small bars differ from the other bedforms because bars originate in response to the local geometry of the flow and therefor may occur singly. They are, however, very similar in scale to the others.

The presence of deep channels in the river (see Chapter V) and the geometry of those channels leads to the formation of very large bars termed cross-channel bars (this chapter). These are much larger in scale than most of the bedforms discussed previously and are very important in the large scale organization of the river. Certain areas on the tops of these bars may become emergent, forming what are termed nuclei

FIG. 19. The conceptual framework of the river deposits. The diagram is discussed in the text.

CONCEPTUAL FRAMEWORK



of new sand flats (see Chapter VI). These nuclei, together with the bars on which they form (and older sand flats in some cases), are termed bar systems.

In places where accretion adds to a nucleus, a sand flat is formed (see Chapter VI). Sand flats are larger and more complex than nuclei. A fully-developed sand flat may bear little resemblance to the nucleus from which it formed.

Several sand flats which are near one another with only shallow channels between them comprise a sand flat complex. These are the most important areas of sediment accumulation in the active river system.

Islands and floodplains are large complex elements which result from long-term processes of stabilization which act on some sand flat complexes.

Although the individual elements are shown as discrete types of features, it should be understood that most grade into closely related elements. The bedforms in the top line appear to be one natural class because they form in response to local hydrodynamic conditions. Bars may form from sand waves in a few cases (see Chapter IV), but in general are more closely related to local topography. They are, therefore, distinctly different from the other bedforms. A complete gradation exists between small bars and large cross-channel bars. They are separated because of the role that the latter play in the formation of the larger elements. The formation of a nucleus on a cross-channel bar at first does little to change the bar, therefore a continuous gradation exists between cross-channel bars and bar systems. A continuous gradation of scale and complexity exists between a simple emergent nucleus through a fully developed sand flat to a sand flat complex. Islands and floodplains are distinctly different forms because they are stabilized by cohesive sediment and vegetation.

This conceptual framework shows the elements which will be discussed later in this thesis and the relationships they have with each other. This framework will form part of the model of sedimentation proposed in Chapter VIII.

CHAPTER IV

THE BEDFORMS IN THE RIVER

INTRODUCTION

To understand sedimentation in the river, it is necessary to understand the bedforms which transport much of the sediment. This involves description and classification of the bedforms, determination of the hydraulic conditions under which each type is stable, and investigation of the distribution of each type in the river.

The bedforms have been subdivided into classes which are believed to represent discrete types of bedforms. The criteria used to classify them are: 1) their sizes and shapes; 2) their hydraulic characteristics. This attempt to establish a classification based on real divisions is in contrast to some studies in the literature. Coleman (1969) subdivided the bedforms of the Brahmaputra River on the basis of amplitude, with entirely arbitrary class boundaries.

Investigation of the South Saskatchewan River resulted in four types being recognized. These are: 1) ripples; 2) dunes; 3) sand waves; 4) bars. This system of classification closely resembles the classification scheme of Costello (1974), and Southard (in Harms <u>et al</u>, 1975) for bedforms observed in flume experiments. However, some differences between the two classifications exist. These differences and the reasons for these will be discussed later in this chapter.

The classifications of Costello (1974), Boothroyd and Hubbard (1974), Southard (in Harms et al, 1975), and this report are summarized in Table 4.

MORPHOLOGY, DISTRIBUTION AND STRATIFICATION OF EACH BEDFORM TYPE

Ripples

These bedforms are the smallest in the system, with amplitudes less than 5 cm and wavelengths commonly less than 30 cm (Fig. 20). Their shapes are variable, with straight-crested, sinuous, rhomboid, and linguoid forms present. Straight-crested ripples are common in very shallow water, becoming more sinuous, then linguoid in progressively deeper water. This is similar to the shallow to deep sequence of ripple shapes reported by Allen (1968). The majority of ripples in the system, however, are linguoid. The straight-crested variety are immature, newly-created forms. In a few localities, wave ripples and aeolian ripples have also been observed.

Ripples occur most commonly in shallow channels, along the margins of major channels, and on submerged sand flats. They may also be present in deep channels, sheltered behind

TABLE 4

Author	1.	2.	3.	4.
Costello	ripples	bars	dunes	--
Boothroyd and Hubbard	ripples	sand waves	megaripples	--
Southard	ripples	sand waves	dunes	bars
Cant (this report)	ripples	sand waves	dunes	bars

This table compares the bedform terminology of several recent authors with that used in this report. Ripples, sand waves, and dunes are believed to be equilibrium bedforms by all authors with increasing flow strength to the right. Bars are non-repetitive, non-equilibrium geomorphic elements.

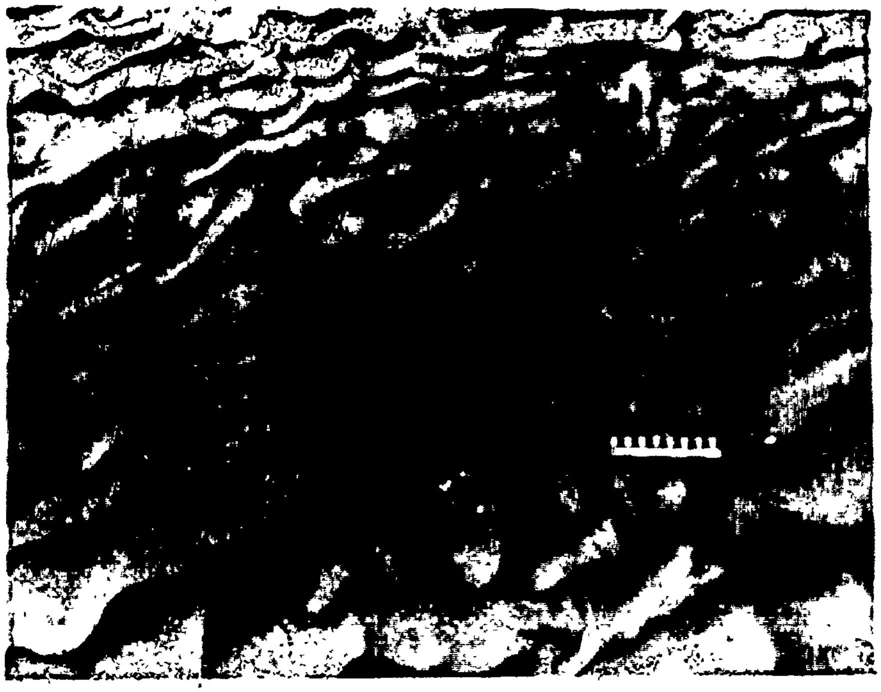


FIG. 20. A train of sinuous-crested current ripples which have irregular amplitudes. The flow was towards the camera. The scale is in centimetres.

large bar fronts where currents are weak. Ripples may occur in large areas by themselves, but more commonly are associated with sand waves. Ripples occur at low flow velocities (next section), so are more common at low stages than during flood events.

The ripples of this study are the same as the ripples of Simons et al (1965) and Southard (in Harms et al, 1975) from flume experiments. Ripples of one type or another are common to most sedimentary environments.

Ripples generate sedimentary structures in the form of ripple cross-lamination. The very common linguoid current ripples deposit small scale (less than 4 cm thick) trough cross-lamination. This structure can be found in the upper parts of the sand flats, in the fill of shallow channels, and in the river banks as part of the vertical accretion deposits.

Sand Waves

These bedforms are very long and low with wavelengths commonly 5 to 10 m and amplitudes 5 to 20 cm (Fig. 21). Along the crest of a sand wave, the amplitude is very consistent, with no scour troughs, spurs, or other irregularities present. In shallow channels, sand waves have straight to gently curving crest lines. On the sand flats, however, they are more commonly rhomboidal in shape. Where many rhomboidal sand waves occur together, they form a cross-hatched pattern.

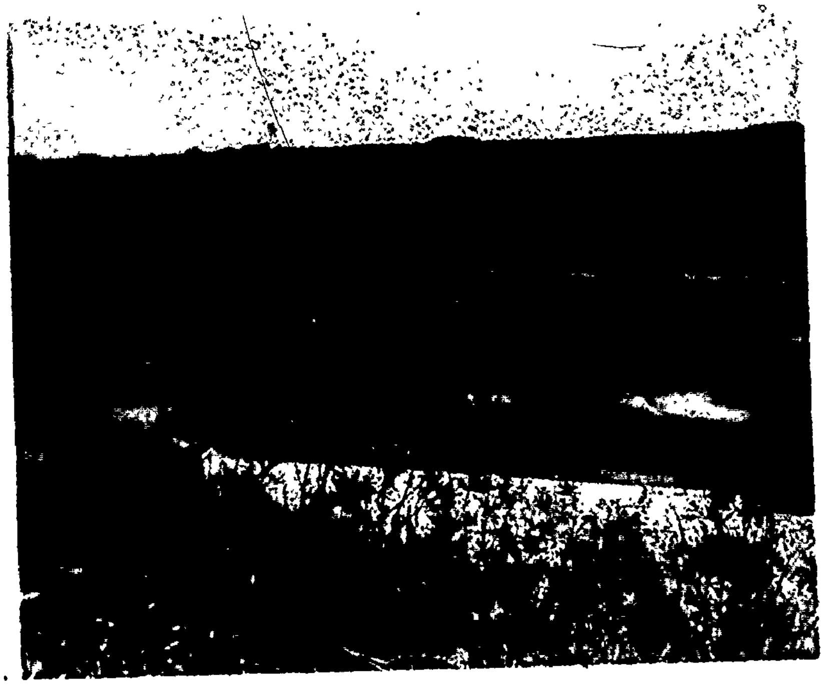


FIG. 21. An area of long, low, rhomboid-shaped sand waves which are covered by ripples. The sand waves have very regular amplitudes with no spurs or scour troughs. Note the serrated appearance of the edge of the sand flat caused by the presence of the sand waves. Flow was from right to left. See also Fig. 4.

In some cases, one limb of the rhomboid will be very much longer and higher than the other, giving the impression of an oblique-to-flow or swept (Allen, 1968) bedform. Sand waves have angle of repose slipfaces when active, but these are rounded off very easily at lower flow stages.

In almost all cases, sand waves have linguoid ripples developed on their stoss sides. The two bedform types appear to be both at equilibrium under the same relatively low flow velocities (next section).

The possible initiation of sand waves was observed in a few localities on the sand flats. A train of almost straight crested ripples developed sharp bends and zones of lower amplitude. These discontinuities in the ripple crests formed two sets of intersecting lines, both oblique to the directions of ripple advance (Fig. 22). These lines resembled the limbs of rhomboidal sand waves. The reason for the formation of these discontinuities is unknown. Very low amplitude (5 cm) sand waves have been observed which were not much larger than the amplitude difference produced at some of the dislocations in the ripple crests. Because of this, along with the similarity in shapes, and the similar locations of occurrence (on top of sand flats), these linear dislocations are believed to be the precursors of fully developed sand waves. The discontinuities in the ripple crests apparently affect the flow so that minor slipfaces may form along some of the lines which they define.

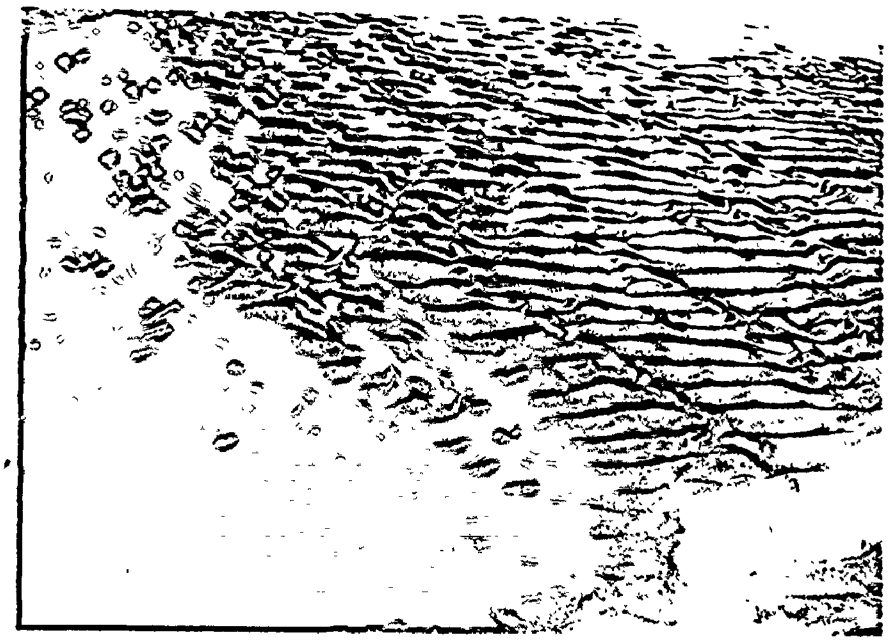


FIG. 22. A train of almost straight-crested ripples which have localized sharp bends and zones of lower amplitude. These discontinuities form two intersecting sets of lines. The more evident set heads to the lower right, and the less evident to the lower left. The ripple direction bisects the angle between the lines.

In a few deeper (1.5 m) channels, straight crested, repetitive bedforms were observed which resembled sand waves. However, these bedforms were up to 30 cm in amplitude and had small dunes developed on their stoss sides. The larger bedforms may have been sand waves, but it is not known whether the assemblage was at equilibrium. If this assemblage was in equilibrium, then small dunes could be co-stable with large sand waves, but not enough data exist to evaluate the problem thoroughly.

Sand waves are extremely common in the system, mainly in the shallower areas such as in minor channels, along the margins of major channels, and on the tops of sand flats. Their presence along channel margins causes the edges of the sand flats to have a serrated appearance.

These sand waves are the same bedforms as the "bars" reported by Costello (1974) from flume experiments. Many similar bedforms have been described from other natural environments, notably by Boothroyd and Hubbard (1974) from a tidal estuary. Other studies which report bedforms which may be the same are Collinson (1970), repetitive linguoid bars; Smith (1971), diminished dunes; Jackson (1976), transverse bars.

Sand waves have characteristic internal structures of small (5 to 15 cm) sets of planar crossbeds (Fig. 23). A set may be very uniform along its length, or it may be highly irregular, with multiple reactivation structures. If traced

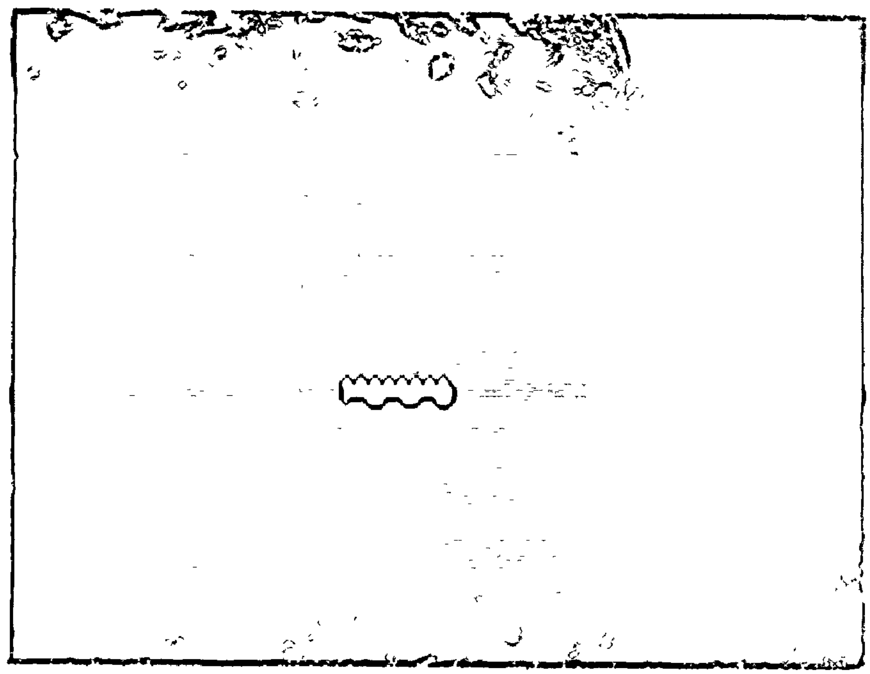


FIG. 23. A ripple-covered sand wave trenched open to reveal the internal stratification, a small planar crossbed set overlain by ripple cross-lamination. Some ripple form-sets are present within the planar crossbed on a reactivation surface. Flow was left to right. Scale in centimetres on top.

far enough back upstream from the slipface, the amplitude of the crossbed set declines until it can no longer be identified. The crossbed sets are very closely associated with ripple cross-lamination which may be superimposed on them, or developed lateral to them. The internal laminations of the small crossbeds are commonly well defined. The sorting necessary to produce these laminations takes place during the migration of the ripples over the stoss sides of the sand waves. Crossbeds generated by sand waves may be found in the upper parts of sand flats, in the fill of shallow channels, and in the river banks, just below the overbank deposits (Appendix 2).

Dunes

These bedforms range remarkably in size, from those 10 cm in amplitude and 40 cm in wavelength, to others 2 m in amplitude and 40 m in wavelength. Compared to sand waves, they are steep bedforms. Dunes show a great deal of variation in the direction transverse to flow, with sinuous to lunate crest line shapes, irregular heights, development of small spurs, and the presence of erosional scour troughs (Fig. 24). This 3-dimensionality of the bedforms is one characteristic which serves to differentiate dunes from sand waves.

Small dunes may have ripples developed on their backs. In some cases, this results from declining flow velocity and superimposition of smaller bedforms (Allen, 1973), but in other cases, the assemblage may be an equilibrium bed

FIG. 24. An area of 3-dimensional sinuous-crested dunes with ripples superimposed on them. Note the scour troughs which are filled by water in some cases. Dunes are rarely exposed, so no better photos of them exist. This figure should be compared to the sand waves in Figs. 4, 24.

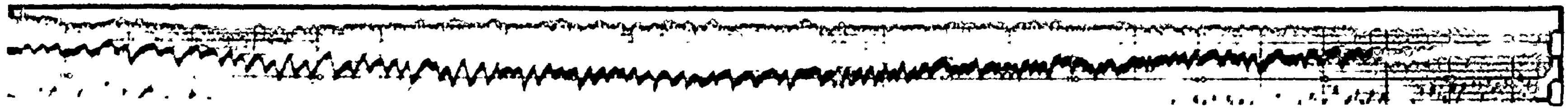
configuration. It can be interpreted as equilibrium because of the length of time it may persist, and because of similar equilibrium configurations in flume experiments (Simons *et al*, 1965).

Dunes occur at higher flow velocities for similar depths than ripples or sand waves. They are present on the beds of most of the major channels in the system where flow velocities are relatively high. The larger dunes are present in the deeper, faster channels with smaller dunes in shallower channels. At high river stages, small dunes may form on the tops of the sand flats.

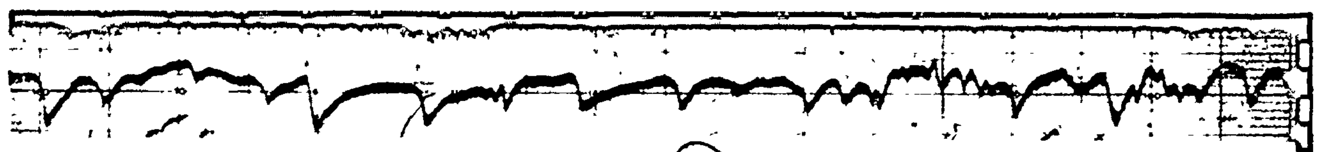
The sizes of the dunes present in a channel depend on the depth and velocity of flow over them. During the flood of June, 1975, the dunes in a carefully monitored channel reacted by becoming larger in both amplitude and wavelength during the rising stage (Fig. 25, 1st and 2nd profiles). At peak flood, very large dunes up to 2 m in amplitude were present with some superimposed smaller forms (Fig. 25, 2nd profile). The depth and mean velocity of the flow over these large bedforms were plotted on a diagram of bedform stabilities established for a tidal situation (Boothroyd and Hubbard, 1974). The depth and mean velocity of the peak flow plotted very near to the extrapolated line separating planed off bedforms from plane bed. This is the reason for the very long amplitudes of these bedforms.

FIG. 25. Four echo sounder profiles made down the same channel during the flood of 1975 (Channel B in Fig. 38). The vertical scale at the right end of each profile is in metres. The length of channel represented by each is the same.

JUNE 23 Q = 1197 m^3/sec 10 m

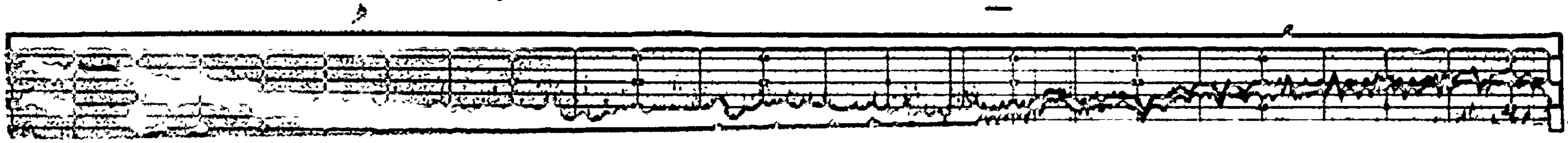


JUNE 25 Q = 1812 m^3/sec 10 m



JUNE 27 Q = 1232 m^3/sec 10 m

JUNE 29 Q = 560 m^3/sec 10 m



As the velocity of the flow declined (Fig. 25, 3rd profile), the large bedforms disappeared, until no trace of the very large bedforms existed (Fig. 25, 4th profile).

The dunes of this study are the same as the dunes of Simons et al (1965). Similar bedforms have been reported from many sedimentary environments.

Dune migration results in the deposition of sets of trough crossbeds (Fig. 26). This has been established by box coring dune-covered areas in shallow (.5 m or less) channels. The dunes present in these channels were small (less than 20 cm) because of the shallow depths. Unfortunately, with the equipment available, it was impossible to box core in the larger channels in the river. However, it is possible to infer the stratification type created by the large dunes in these channels. Dunes generate trough crossbeds because of their irregular shapes, in particular because of the presence of spurs and scour troughs. Small dunes of this type generate circular boils in the flow which break the surface of the water. Straight crested bedforms such as sand waves do not. The large dunes in the channels cause extremely large boils (up to 3 m diameter) to break the surface. Therefore, it is inferred that the bedforms were strongly 3-dimensional and generated trough crossbeds.

Figure 25 (2nd profile) shows that the large dunes at flood peak had deep scour troughs. These troughs cut more deeply below the average bed level than the troughs created

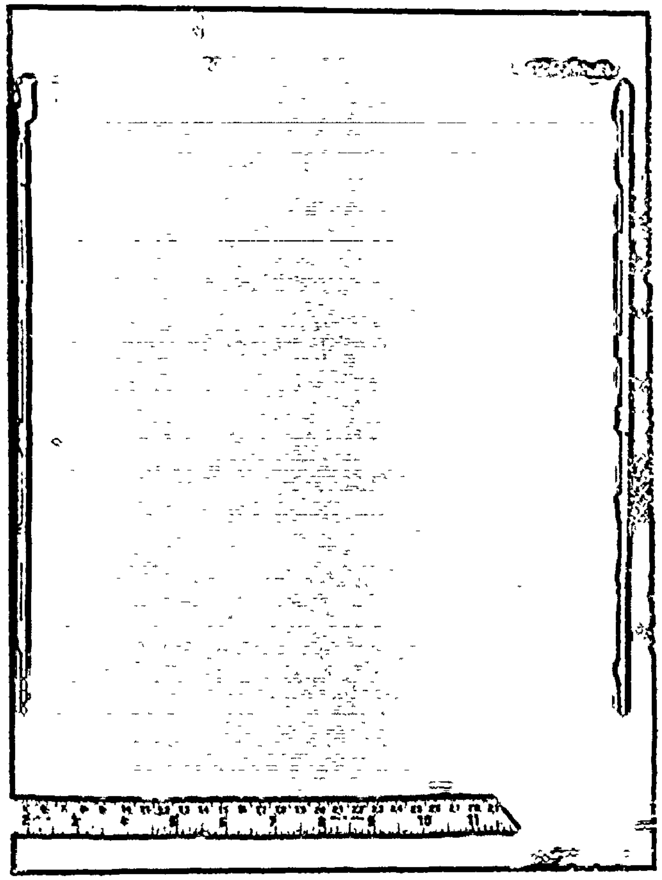


FIG. 26. A photo of a boxcore taken in a shallow, dune-covered channel. Small trough crossbeds are present in the core, deposited by the dunes. The boxcore is 30 cm on each side.

before or after the flood peak. Therefore, previously deposited smaller trough crossbeds would be scoured out and replaced by the large trough crossbeds of the dunes during peak flow. The smaller troughs of the bedforms active during the falling stage could not erode deep enough to remove the trough crossbeds created by the largest dunes. The sizes of the dunes at peak flow cause these selectively preserved trough crossbeds to be very large.

Bars

These bedforms are not equilibrium features in the sense that ripples, sand waves, and dunes are. These other bedforms are created by the flow under a specific range of hydrodynamic conditions, and disappear outside that range (in general). Bars, however, are very persistent forms which may survive long periods of widely differing flow conditions.

Bars are non-repetitive slipface-bounded wedges of sediment (Fig. 27), similar to the laboratory deltas of Jopling (1965) and the transverse bars of Ore (1963) and Smith (1970). Bar fronts are straight to linguoid in plan view, but may become irregularly shaped because of small lobes building forward as a response to changing river stage (Collinson, 1970). Sediment is transported over their tops by ripples, sand waves, dunes, or as plane bed, then avalanches over the margins. Where the flow over a bar front makes an angle of less than 45° (in plan view) with the crest of the bar, no slipface is present, only a low angle slope.

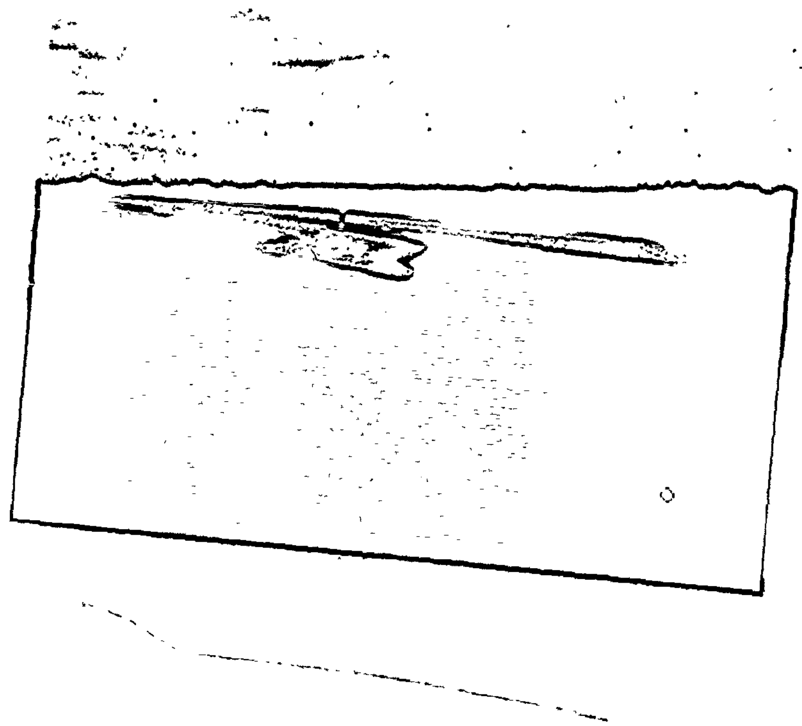


FIG. 27. A large bar which has been driven laterally onto a sand flat. The top of the bar is covered by ripples. Falling water marks are present on the slipface.

Bars in the river range in height from 15 cm to 3 m or more, but the height is a function of the local topographic relief and is unrelated to flow depth or strength. They range in length (along the slipface) from small forms which die out in 10 m to those which extend several hundred metres diagonally across the river.

The major control on the formation of bars is the geometry of the situation, rather than the hydraulic characteristics of the flow. They form as a result of the area of the flow expanding, a condition which arises because of the configuration of pre-existing topography in the river.

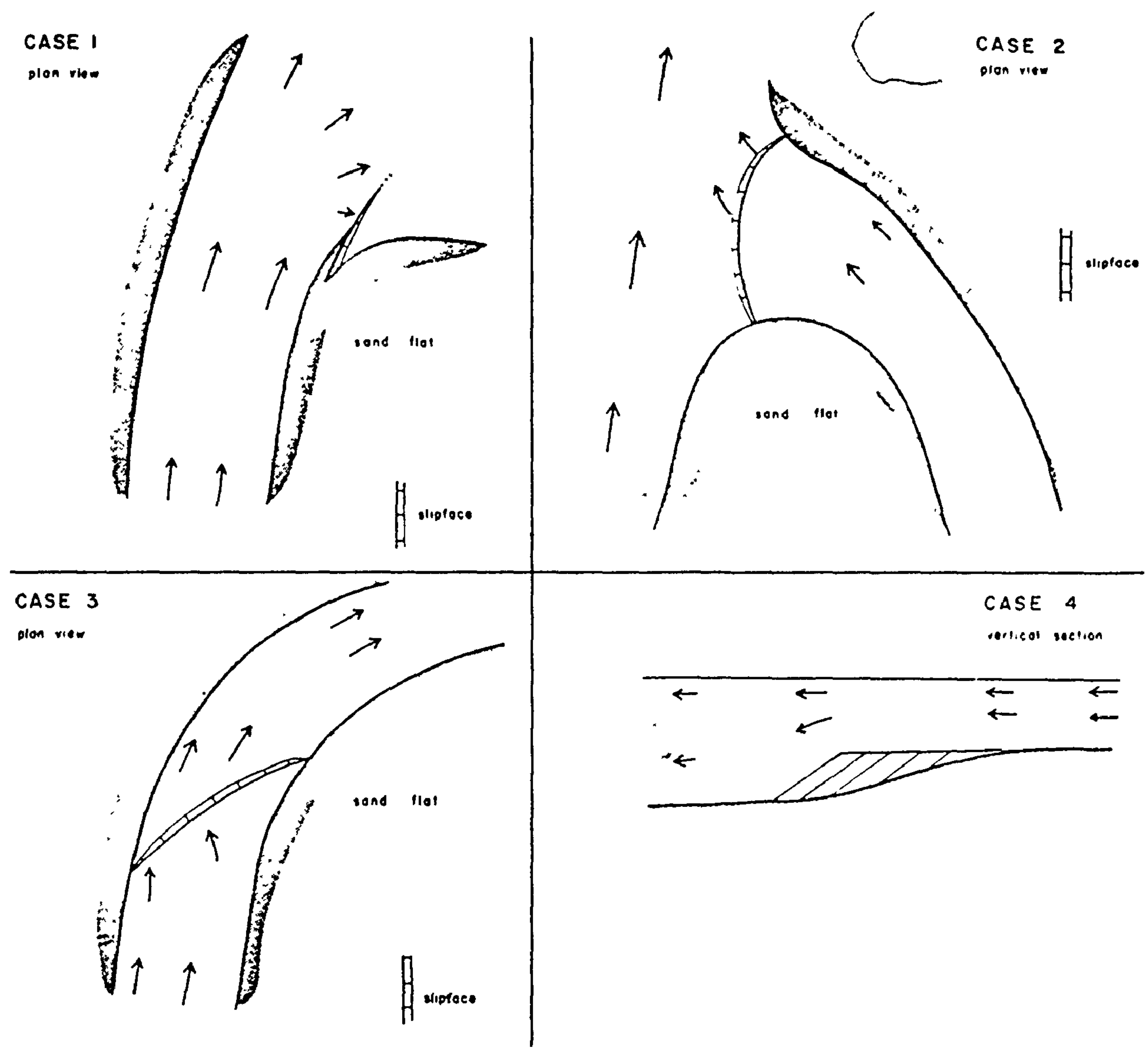
Bars form at four major types of localities in the river: 1) at areas of increased flow width; 2) at channel junctions; 3) at bends in channels; 4) at locations of vertical flow expansion. These are illustrated in Fig. 28.

Case 1 commonly results where the flow expands around the lee side of a sand flat. An inward advancing slipface forms at the downstream end of the sand flat. This is similar to the scroll bars of Sundborg (1956) and Jackson (1976) in meandering systems. This mechanism is also similar to the mode of formation of side flats (see Chapter VI) in which the flow also expands laterally.

Case 2 occurs where two channels of unequal depth join. The bar extends from sand flat to sand flat across the mouth of the shallower channel. These bars form because the flow

FIG. 28. The locations of bar formation in the river. They are explained fully in the text.

BAR FORMATION



from the minor channel expands laterally and vertically into the deeper water of the larger channel, dropping its sediment load as a small delta-like body.

Case 3 is the result of a bend in the channel which forces the flow to change direction. As the flow enters the bend, the apparent width of the channel increases. This occurs because the bend in the flow lags behind the bend in the channel and the flow enters the bend heading across the channel. Because of the shape of the bend, the width of the flow becomes very large and a bar front forms. This does not occur in most meandering channels because the inner bank progrades and cuts down the effect of the apparent increase in width. In the wide, shallow channels in the South Saskatchewan River, spiral flow will be very poorly developed, so little accretion takes place on the inner bank. After the bar front is established, it diverts flow to the outside of the bend, causing the apparent width of the flow to be increased still further.

This same pattern can be seen on vastly differing scales, ranging from bars in a 30 cm deep drainage channel on a sand flat, to major bar systems spanning much of the river system (Chapter III).

Case 4 occurs very commonly at the downstream margins of sand flats when they are inundated at high stage. As the flow passes over the downstream end of the sand flat, it expands into deeper water and drops its sediment load. A slipface is established which may advance downstream, causing the sand flat to lengthen.

Many of the bars in the system could be interpreted as resulting from more than one of the above causes. This is in part a reflection of the fact that bar formation in all cases results from flow expansion, and more than one cause of this may be present in a given instance.

The growth of a bar results in the deposition of a set of planar cross-stratification (Fig. 29). This has been discussed in detail by Smith (1972). In many cases, unsteady flow may cause the formation of reactivation structures within a planar crossbed set. Some bars generate different types of stratification because of their irregularly shaped crest lines. The simplest kind of irregularity is a curved front, with different avalanche directions at different locations along the front (Fig. 30a). A more complex kind of irregularity is the presence of small points and re-entrants on an oblique bar front (Fig. 30b, 30c). Where the flow passes over the oblique part of the slipface (marked o), spiral flow occurs which generates a current moving along the bar front towards the point. This current transports sand in the form of ripples which are deposited at the point forming a spur. One side of the spur, therefore, is depositional (marked d on Fig. 30b, 30c). Because of the re-entrant on the other side of the point, flow is concentrated, with the result that the other side of the spur is erosional (marked e on Fig. 30b, 30c). The spur may be either erosional (Fig. 30b)

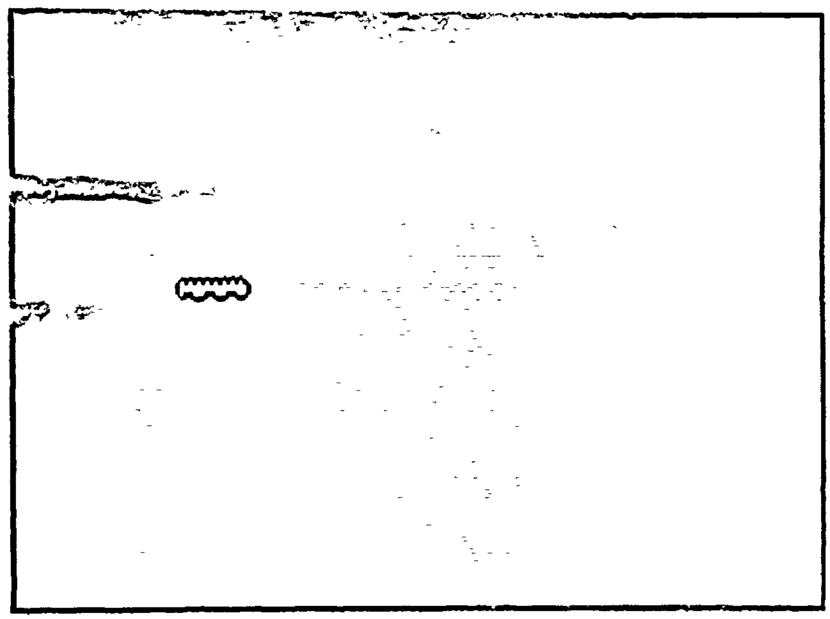
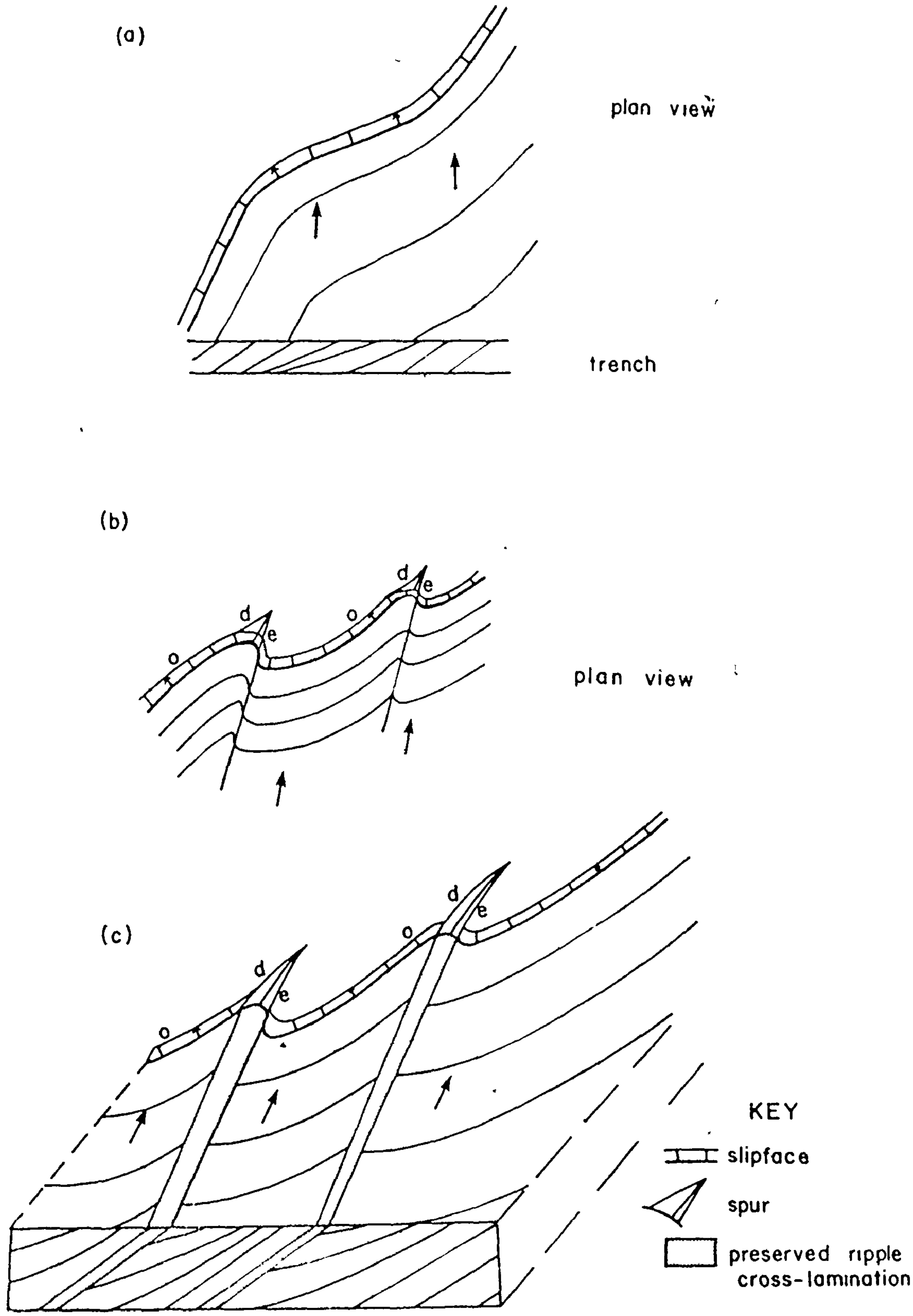


FIG. 29. The internal structure of a small bar, one planar crossbed set capped by ripple cross-lamination. In the middle of the set, a series of lower angle laminations are truncated by a mud-covered reactivation surface. The top scale is in centimetres.

FIG. 30. A diagram of the irregularities present in some bar fronts and their effect on stratification. The letters in (b) are explained in the text.


(a)
plan view
trench
(b)
d
e
o
plan view
(c)
KEY
slipface
spur
preserved ripple cross-lamination

or may deposit ripple cross-lamination (Fig. 30c), depending on the relative strengths of the eroding and depositing currents. In a very few cases where the depositing currents were much stronger, the eroded margin of the spur became an avalanche face, with a small crossbed set formed.

A trench through the bar of Fig. 30a shows foresets of apparently variable dip. This variation occurs because different parts of the bar are advancing in different directions. Smith (1972) noted this effect of curved bar fronts in bar deposits in the Platte River.

The bar in Fig. 30b has deposited curving stratification, which is segmented by erosion surfaces generated at the spurs. Because of the curve of the bar front between the spurs, the stratification resembles a trough crossbed in plan view. Many of these were observed on the sand flats after the recession of the flood of 1975. These crossbeds, however, do not have trough-shaped lower bounding surfaces. They are planar sets, but are segmented by the erosion surfaces.

In Fig. 30c, the two spurs have deposited ripple cross-lamination, which is preserved within the other deposits of the bar. Because the direction of the bar front varies consistently between the spurs, the apparent dip of the foresets also varies consistently. The bar deposits, therefore, in a section almost transverse to flow, consist of segments beginning with ripple accretion developed on a low angle erosion surface, followed by steeply dipping foresets which flatten off, and are finally truncated by another erosion surface.

This type of structure could be mistaken for a reactivation surface, which implies fluctuating stage (Collinson, 1970) with erosion and/or ripple deposition at low stage and further bar growth at higher stage. These types of pseudo-reactivation structures have not been reported previously as resulting from irregular bar crest line shapes.

MORPHOLOGIC AND GENETIC RELATIONSHIPS BETWEEN BEDFORM TYPES

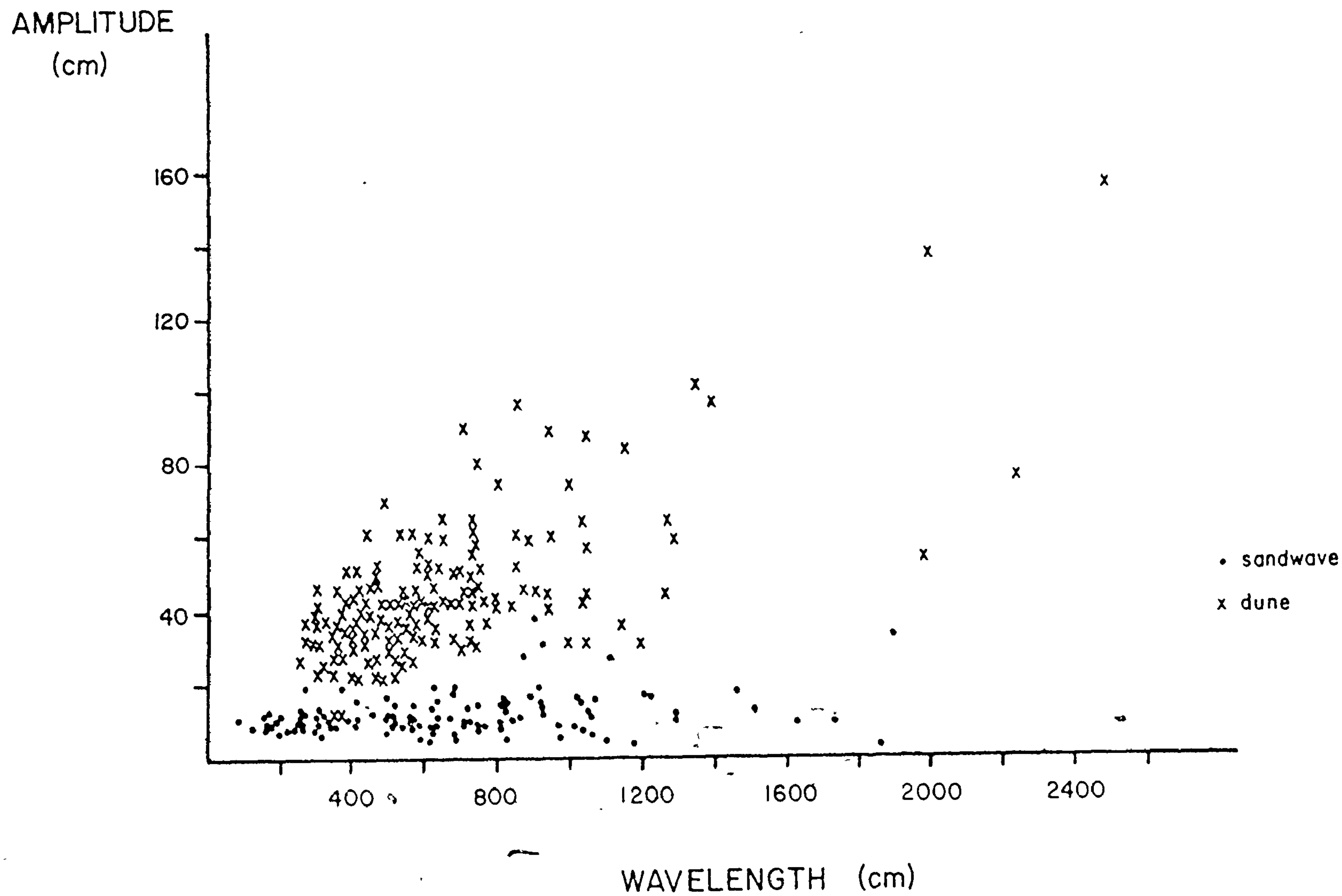
(a) Sand Waves and Dunes

Allen and Collinson (1974) have denied the existence of lower flow regime equilibrium bedforms other than ripples or dunes. They believe that all other forms are disequilibrium dunes. However, the sand waves of this study appear to be distinctly different from the dunes in the system.

Figure 31 is a plot of amplitude vs. wavelength for many bedforms in the river. This figure was prepared by compiling two distinct types of data, one type from direct measurement of exposed bedforms, and the other from measurement of echo sounder records. In order to make the data from the echo sounder records more compatible with the data from the exposed bedforms, two criteria for measurement of the echo

FIG. 31. A graph of amplitude vs. wavelength for sand waves and dunes. Sand waves have much lower amplitudes.

BEDFORM HEIGHTS vs LENGTHS



sounder records were established. These were: 1) to avoid diagonal traverses across bedforms, only those which appeared to have angle of repose slipfaces were measured; 2) where two or more scales of bedforms were present, smaller superimposed forms were ignored. While this method may be criticized as somewhat subjective, no completely objective method could be devised to overcome the limitations of the echo sounder data.

Identification of bedform types on the echo sounder records was done by a variety of methods. These methods are listed here:

1) direct observation of the shapes and variations in the crest lines of the bedforms;
2) the presence of very large circular boils in the flow was taken to be indicative of dunes on the bed (see section on dunes earlier in this chapter);
3) the presence of scour troughs below the general bed level on the sounder records indicated dunes.

Figure 31 shows that sand waves have distinctly lower amplitudes than dunes for similar wavelengths. Sand waves rarely build up over 30 cm in amplitude. The amplitudes of the dunes generally increase along with the wavelengths, but not with a well-defined relationship. A clear morphologic distinction, therefore, separates sand waves from dunes.

In a series of papers (Allen, 1973, 1974; Allen and Collinson, 1974), the concepts of phase lag of bedforms and bedform disequilibrium have been presented. Allen and Friend (1976) have introduced the concept of the relaxation time of a bedform. This is the time required for the disappearance of a larger non-equilibrium bedform by sediment transport at a lower flow state. This concept has been used to prove that the sand waves in the South Saskatchewan River are not relict dunes.

After the flood peak of 1975, the flow in the river was very steady for a period of 25 days. During this time, no daily fluctuations in stage greater than a few centimetres occurred. The average sediment transport rate of ripples was calculated with the use of typical depth and velocity conditions for ripples by the Kalinske method (Raudkivi, 1967) and by the use of an empirical ripple velocity equation cited by Allen and Friend. The calculated rate was .1 to .3 cm^3/sec/cm. Allen and Friend assumed a simple model for a dune shape, with the volume of the scour trough equalling the volume of the dune. They showed that the minimum cross-sectional area which must be infilled to obliterate the dune was

$$A_{min} = .167 \, L \, H$$

where L, H, are the wavelength and amplitude of the dune.

For the case of a moderate-sized dune of L = 4 m, H = 40 cm

$$A_{min} = 2672 \text{ cm}^2.$$

Therefore, the time of destruction of this is from 2.5 to 7.5 hours.

However, the sand waves showed no sign of disappearing over the 25-day period, and, in fact, were very common throughout the system at the end of this time. This indicates that sand waves are not relict dunes, but a separate bedform type.

(b) Sand Waves and Bars

During the course of the field work, it was observed that small bars are very similar in appearance to sand waves. The two bedform types can be differentiated in most cases by the fact that sand waves are repetitive, whereas bars are solitary and are related to the local topographic configuration.

In some cases, however, it was observed that a line of sand waves changed through time into bars. This occurred in two different types of locations in the system; on the sloping upstream portion of sand flats, and at the downstream margins of sand flats. In both cases, rhomboid sand waves migrating into shallower water reached areas of such low flow velocities that they ceased to be active. Other sand waves migrating near them in slightly deeper water advanced slightly farther, until they also became inactive. Because of the low slope of the bottom, and the rhomboid shape of the sand waves, the corresponding limbs of the sand waves became aligned, forming an inactive ridge. At the next minor rise in stage, vertical flow expansion over the step created by the sand waves formed a bar front. This process is illustrated in Fig. 32.

It is not implied here that all bars in the system result from the presence of inactive sand waves. Only a few small bars originate in this manner, but the process shows the close relationship between bars and sand waves.

Southard (in Harms et al, 1975) has stated that differentiating between sand waves and certain kinds of bars is difficult in shallow rivers. The differences between the sand waves and bars in the South Saskatchewan River are summarized in Table 5.

BEDFORM HYDRAULICS

Velocity profiles were measured over many bedforms to attempt to define the hydraulic conditions under which each bedform type is stable. These profiles were measured from the anchored boat with a Price-type AA current meter on a rod. Before a profile was measured, certain checks were made: 1) that the sediment comprising the bedforms was being actively transported; 2) that the bedforms were not in obvious disequilibrium with the flow (i.e., nearly emergent or being eroded). While these checks do not provide assurance that the bedforms were in equilibrium with the flow, it is believed that in most cases, equilibrium was approached reasonably closely.

FIG. 32. The process of forming a small bar front from a series of sand waves. The diagrams are fully explained in the text.

The strike and dip symbol indicates the slope on the river bed.

BAR FORMATION

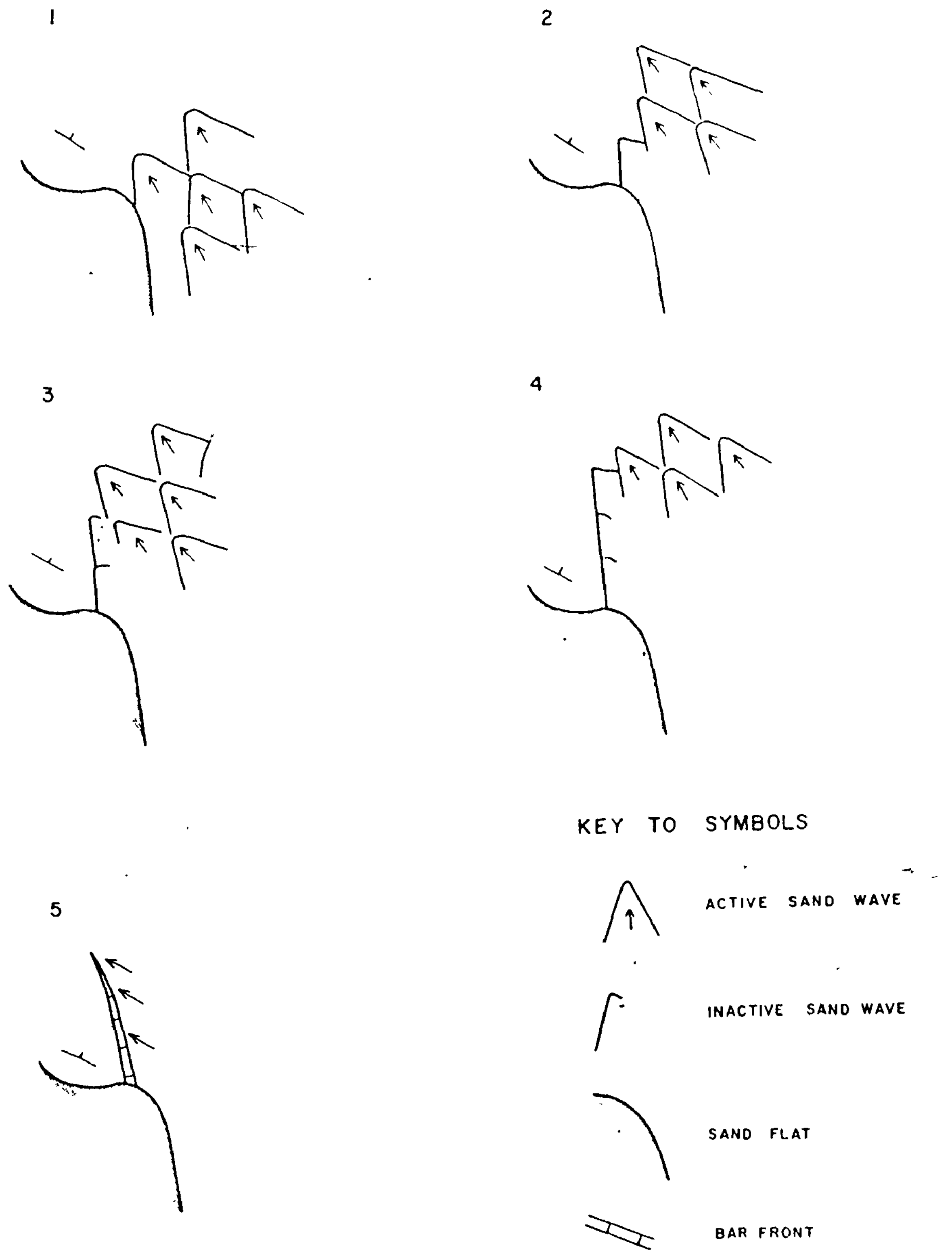


TABLE 5

COMPARISON OF SAND WAVES AND BARS

Sand Waves	Bars
- equilibrium bedforms	- in most cases, not at equilibrium
- repetitive	- solitary
- form in response to the hydrodynamic conditions	- form because of the geometry of the situation
- less than 30 cm high	- range from approximately 15 cm to 3 m
- ripples cover their stoss sides	- any bedform may occur on their tops

The data from these hydraulic measurements is given in Appendix 3. From these velocity profiles, the shear stress and the shear velocity were calculated. These parameters did not show patterns which could be interpreted, possibly because of measurement problems. The current meter made an average velocity measurement over one minute. A complete profile required 5 to 10 minutes to complete. The scatter in the measurements possibly resulted from intermediate term turbulent fluctuations in velocity. The mean velocity of the flow was the parameter which best represented flow strength and showed interpretable patterns. This was calculated by averaging the velocities measured at .2 and .8 of the depth.

Ripples

Because ripples are found on the stoss sides of sand waves, apparently in equilibrium, no separation of the two bedform types can be made. Data obtained from areas of ripples alone (without sand waves) plotted throughout the sand wave field, confirming that no hydraulic separation of the two bedform types is possible. Costello (1974) and Southard (in Harms et al, 1975) also note the close association of ripples and sand waves, but they illustrate a ripple field at lower velocities than the sand wave field. This could not be detected in the South Saskatchewan River. It should be noted, however, that sediment size has an effect on the type of bedform developed. This effect is not well known for sands of mean diameter .3 mm (Southard in Harms et al, 1975, p.21).

Sand Waves and Dunes

As was stated in the last section, sand waves are co-stable with ripples, and occur at relatively low flow velocities. Dunes occur at higher flow velocities than these other bedforms. All the data gathered for sand waves (with ripples) and dunes is plotted in Fig. 33. A clear velocity distinction for any depth exists between sand waves and dunes, indicating that the two types of bedforms are hydrodynamically distinct.

A degree of overlap of the types exists at a depth of 80 cm. This may result from one or more of the following causes: 1) the presence of disequilibrium bedforms; 2) errors of measurement of mean velocity because of turbulent velocity fluctuations; 3) mis-identification of bedforms at times when the channel bed could not be seen clearly.

The transition from sand waves to dunes occurs at velocities 5 - 10 cm/sec lower than those reported by Southard (*in* Harms *et al*, 1975). This is due to the differences in the grain sizes of the sediment, .3 mm in the river vs. .4 mm and coarser in the other case.

The differences between sand waves and dunes are summarized in Table 6.

OTHER BEDFORMS

During the flood of 1975, a flat or plane bed was present on some sand flats. A combination of high flow velocities and shallow depths caused this upper flow regime bed configuration to occur.

FIG. 33. A plot of depth vs. velocity for active dunes and sand waves. The sand wave field also includes ripples. The line on the graph is the line separating sand waves (bars) and dunes reported by Costello (1974).

BEDFORM HYDRAULICS

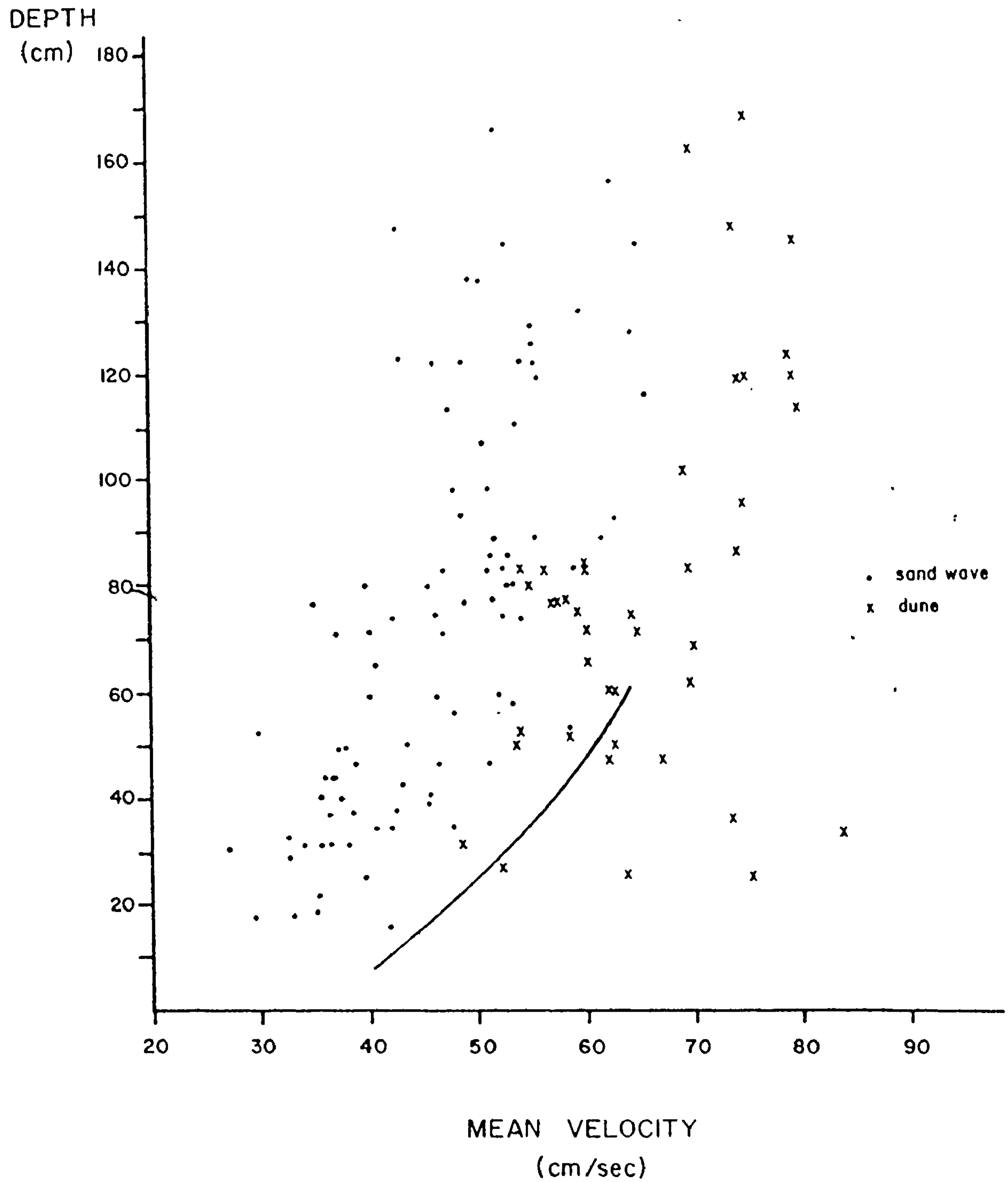


TABLE 6

COMPARISON OF SAND WAVES AND DUNES

Sand Waves	Dunes
- straight to rhomboid in plan view	- sinuous to lunate in plan view
- very regular height all along the slipface	- irregular height because of the presence of spurs and scour troughs
- low amplitude	- higher amplitudes which increase with the wavelength
- occur at lower flow velocities	- occur at higher flow velocities
- common in the higher, shallower parts of the river	- common in the deep channels
- generate small planar crossbeds	- generate trough crossbeds of varying sizes

The plane bed, in most cases, resulted in the deposition of horizontal parallel lamination with parting lineation exposed on the surface of some laminations. However, where the original surface of the sand flat was sloping, sets of laminations with shallow dips were formed (Fig. 34). In a few locations, the laminations dipped steeply (up to 20°) into pre-existing scours (Fig. 35). The cross-laminations formed in this manner can, in many cases, be traced laterally into horizontal laminations in both directions. As the scours became filled by the laminations, the amount of relief was diminished, and the laminations flattened off to a plane bed.

No plane bed in the channels was detected by echo sounding. However, as has been discussed previously, the long bedforms at flood stage were flattened because they were in the transition zone to upper flow regime. If discharge had been greater, and flow velocities higher (hydraulic geometry, Chapter II), plane bed on the channel bottoms might have occurred.

Plane bed and very small (less than 3 cm amplitude) antidunes have been observed in minor drainage channels on the sand flats during falling stage. Because of their size and short period of existence, these forms are of little importance.

FIG. 34. Low angle parallel laminations overlying a zone of irregularly rippled sediment. The parallel laminations are dipping off laterally into a channel. The top scale is in centimetres.

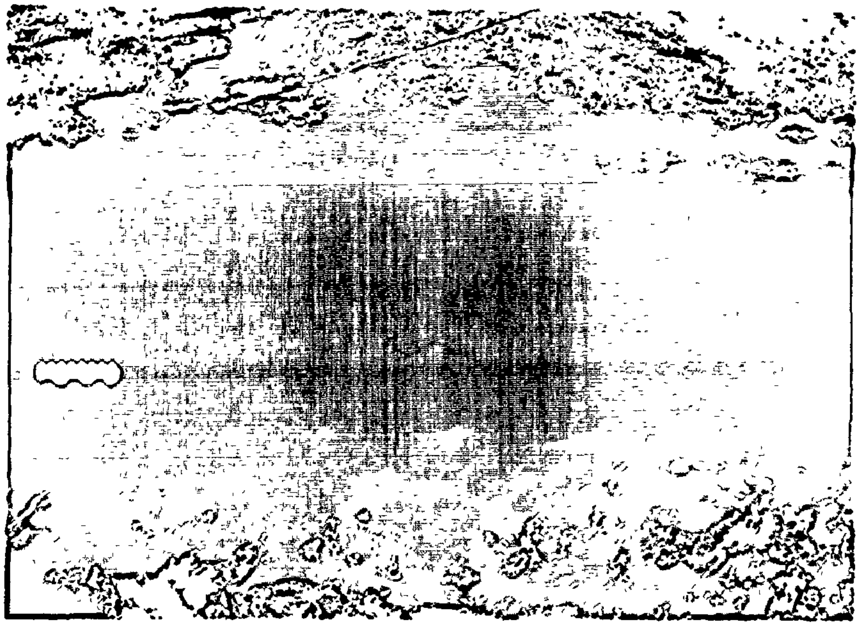


FIG. 35. Parallel laminations on the right assume a dip in the left part of the photograph. When traced laterally, it can be seen that this slope forms one side of a large trough. Upper scale is in centimetres.

CHAPTER V

THE CHANNELS

INTRODUCTION

The channels in the river system are the conduits through which most of the water and sediment discharge is transmitted. Channels are also the loci of formation of new sand flats (Chapters III and VI). The survival or disappearance of newly-formed sand flats depends mainly on changes in the positions and directions of the channels around them (Chapter VI). To develop an understanding of sedimentation in the river, therefore, it is necessary to investigate the channels.

DESCRIPTION OF THE CHANNELS

As was discussed briefly in Chapter IV, the channels have been divided into two groups, major and minor channels. At any locality, only one or two major channels exist, but up to five minor channels may be present (Figs. 13, 36). The two types are treated separately for the purpose of clarity, but there is considerable gradation between them. On the tops of large bar systems, major channels may divide several times, essentially splitting into a number of minor channels. Most of the actual braiding (division and rejoining of channels) is accomplished by these minor channels. Major channels branch and reunite only rarely.

Major Channels

The major channels in the river system range in depth from 2 to 3 m below the nearby sand flats. In a few localities where a channel is confined laterally (i.e., near a stable bank), depths up to 5 m have been measured. Widths of these major channels vary from 70 to 200 m. Width to depth ratios are in the range 25:1 to 100:1. These figures are very approximate because it is impossible in many cases to define exactly the edge of a channel where the channel bed slopes gradually upward onto a sand flat.

The axes of the major channels trend very close to the local river direction, averaging only 13° from this. Where the main flow crosses the system laterally, the major channel commonly divides into several minor channels (Chapter III), accounting in part for the low dispersion of directions of the major channels. These channels also have low sinuosities, commonly less than 1.1.

The beds of the major channels are covered, in most cases, by dunes, with ripples and sand waves along their margins (Chapter IV). In the deeper, swifter channels, the dunes are large (up to 2 m amplitude; Fig. 25), but in shallower, slower channels they never build up to these amplitudes (Appendix 4). The sizes of the dunes in a channel depend to a large extent on the depth of flow in the channel (Chapter IV), and therefore on the topographic elevation of the channel bed. In general, larger dunes are present on the lower channel beds, and smaller dunes on the higher beds. This is important in the consideration of the stratification developed in channel deposits.

At many localities in the major channels, large bars are present. These bars are directly related to the pre-existing topographic configuration in the local area, as discussed in Chapter IV.

Most bars have straight to curving crest lines, which may be very oblique to the flow over them, similar to those of the bars illustrated in Chapter IV. However, in some channels, linguoid bars are present (Figs. 15, 38a) which resemble those illustrated by Collinson (1970). These linguoid forms are not en-echelon; instead, each one appears to be attached to the one immediately upstream of it. The presence of one bar apparently diverts flow laterally, so that flow expansion around it creates a new bar. These linguoid bars are, therefore, interpreted as moderate to low stage features. They are much less common in the river than the other types of bars (Chapter IV).

<u>Minor Channels</u>

The minor channels in the river system are those which flow within sand flat complexes, and over major bar systems. They range in depth from a few tens of centimetres to approximately 1.25 m below the surrounding sand flats, and in width up to 125 m. Their width to depth ratios vary from 40:1 to

200:1, so they are proportionally wider than the major channels. Again, these figures are approximate.

The directions of these minor channels are very much more divergent than those of the major channels, with the average deviation from the river direction being 30°. This value does not take into account the smallest drainage channels, but only those which branch from and rejoin major channels. Minor channels are commonly more sinuous (values ranging up to 1.3) than major channels, with pronounced bends, but are not truly meandering because of their wide and shallow nature. The spiral flow of meandering channels appears to be poorly developed in them, probably because of their very shallow depths (Bridge, 1976).

The minor channels have small dunes or the assemblage of sand waves and ripples on their beds, depending on the depth and velocity of the flow in them. Small bars are also very common, particularly at the downstream ends of these channels where the flow expands into deeper channels. These channels may be completely blocked off by bars which build up at high stage. This process will be discussed in more detail in Chapter VI.

THE ORGANIZATION OF THE CHANNELS

The organization of the channels has been partly discussed in Chapter III. In this section, individual channels will be considered, and also smaller channels. However, some overlap with Chapter III is inevitable.

The fundamental organization of the channels is created by the presence of large bars and sand flat complexes. As discussed in Chapter IV, the bars are present where channels bend, join, or widen. Consideration of any aerial photo (Figs. 13, 38) shows that bars are very common in these types of localities in the river. Because bars are vertical accumulations of sediment, they constrict the flow over themselves (Smith, 1970). Therefore, channels over the bars are relatively shallow. Immediately downstream of bar fronts, channels are very deep in many cases. This occurs for one or more of the following reasons: 1) sediment is trapped where it avalanches over the bar front, with reduced sediment supply downstream; 2) oblique or irregular bar fronts constrict the flow laterally so that high velocity currents immediately downstream maintain a deep channel; 3) the bar builds into deep water, where a small channel enters a larger one.

In Fig. 36, the shallow and deep areas of the channels have been indicated. If a channel is traced downstream, a series of deep to shallow sequences is encountered. These channel sequences are irregular in length and occur in channels of markedly different scales, from the smallest to the largest in the river system. Their formation is largely controlled by the pre-existing topographic pattern of channel shapes and sand flat positions. For these reasons, the deep to shallow sequences are believed to be different from pool

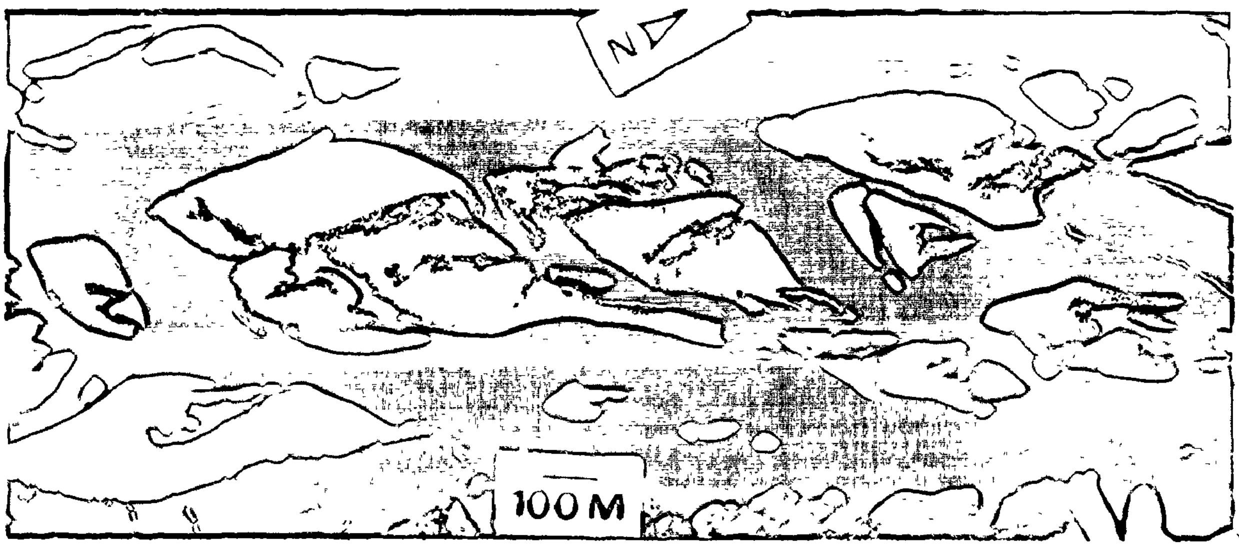


FIG. 36. Air photo showing shallow (S) and deep (D) areas of channels flowing around a sand flat complex. (Photo 147)

and riffle sequences which have quasi-regular spacings and are more closely controlled by hydrodynamic conditions (Leopold et al, 1964).

In the major channels, the shallows on the tops of the bars are the major loci of formation of new sand flats (Chapters III, VI). After a sand flat has developed, it then becomes an obstacle to flow, and new bars may form in response to its presence (Fig. 37). These small secondary bars may confuse the simple pattern of deep to shallow sequences reported above.

The bars are best defined and simplest immediately after the recession of a flood. After several months of variable flows, the single bar front commonly disappears, and is replaced by a series of smaller bars.

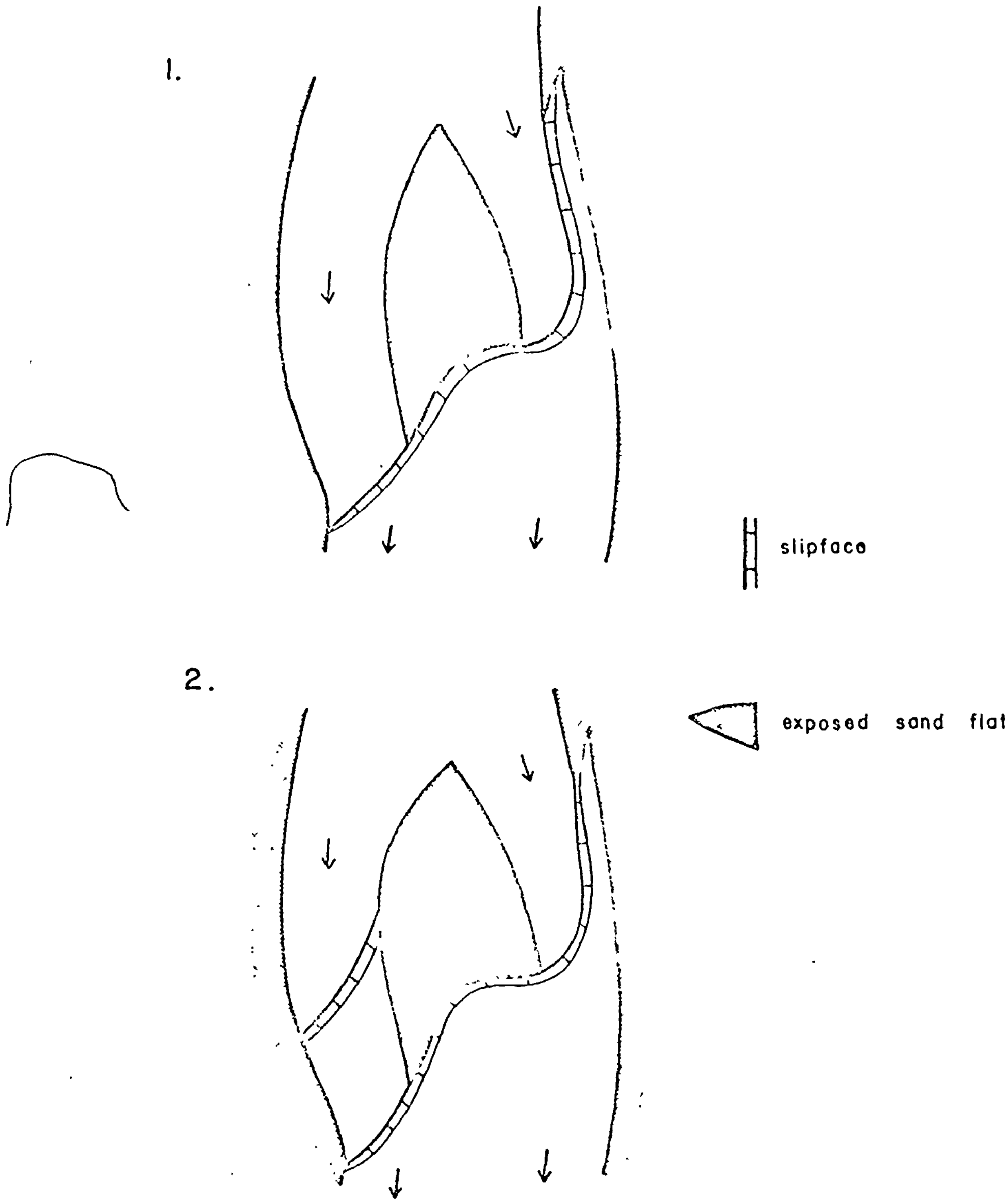
In the minor channels, bar formation is more commonly related to channel bends, rather than splitting and rejoining of the channel. In a case where a minor channel flows in a narrow gap, the flow spills from side to side, forming a pattern which closely resembles alternate bars. This happens only in these narrow erosional gaps, and may represent a tendency towards meandering in these channels.

EFFECTS OF THE ORGANIZATION ON THE BEDFORMS

The organization of the channels has a direct control on the bedforms present on the beds of the channels. This occurs because the depth and velocity of the flow are affected

FIG. 37. The formation of secondary bars resulting from the presence of a sand flat.

SECONDARY BAR FORMATION



by the channel shape which is largely controlled by the organization of the channel. Flow depth and velocity are two of the most important parameters involved in controlling the type and size of bedforms (Chapter IV).

In the deep areas of the major channels, dunes are present at all but the lowest discharges. The four echo sounder profiles shown in Fig. 25 were made in this portion of a channel sequence. As the channel shallows in the downstream direction, the amplitude of the dunes diminishes. Continuous echo sounding the length of one channel sequence showed that the amplitudes of dunes in the deep area (3 m depth) averaged 40 cm, while those in the shallow areas (1 m depth) averaged 20 cm. Although there does not appear to be a unique relationship between flow depth and dune height in this river (see Fig. 25) or in others studied (Allen, 1976), dunes are generally smaller in the shallower parts of the system at a specified discharge.

In a few very deep parts of the system, i.e., where two channels join and converge against a stable bank, no large bedforms are present (Appendix 4, profile 3). These deep areas occur very rarely, and are relatively limited in areal extent, so they are not expected to contribute significantly to the stratification types present in channel deposits.

In minor channels, small to moderate sized dunes (less than 30 cm amplitude) are present at most discharges. The dunes in the smaller channels also build up at high discharges, but not as much as in major channels. In the shallows of minor channels, ripples and sand waves form the more common bedform assemblage, but small dunes may also be present in some of these localities.

Because the minor channels are topographically high (relative to the major channels), they are affected more by stage changes. At very low discharges (less than 100 m^3/sec) flow down some of these channels virtually stops. In the deeper areas of these channels, the flow ceases to move bedload, and fine-grained suspended sediment is deposited. In the shallow portions of these channels, some areas become emergent, with one or more narrower channels forming. The flow in these smaller channels is sufficient in many cases to transport bedload as ripples and sand waves.

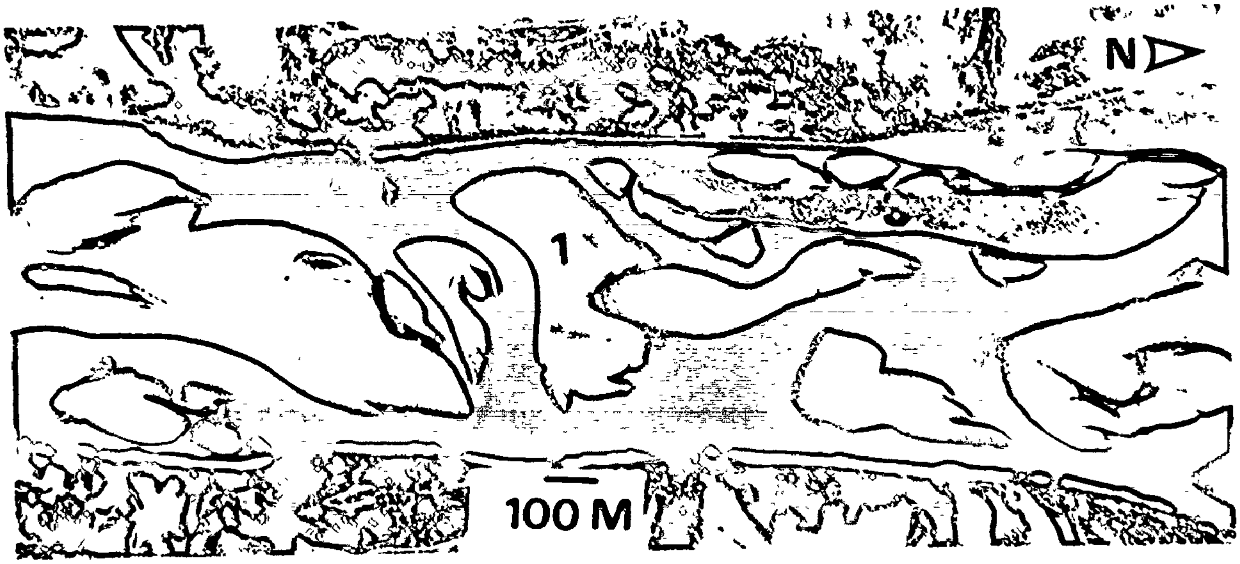
CHANNEL SHIFTING

In Fig. 38, two air photos of the same reach are shown. The upper photo was taken in October, 1967, and the lower in September, 1971. Comparison of these photos shows that some channels in the river systems change positions laterally over a period of years.

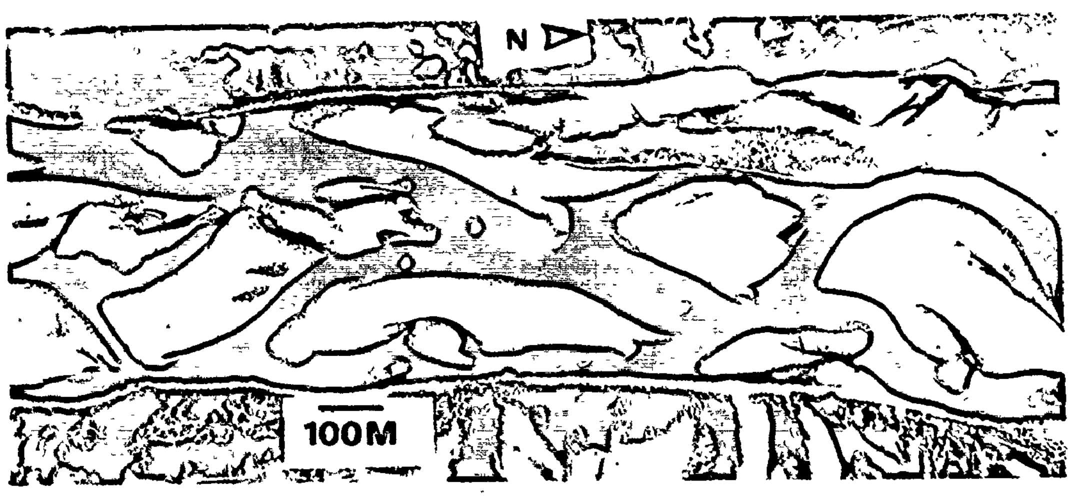
In some cases, the channels migrate laterally by deposition on one side of the channel and erosion on the other. One location where this is interpreted as happening is indicated on these photos with the letter M and an arrow showing the direction of migration: the channel is apparently

FIG. 38. Two photos of the same reach, (a) taken in 1971 and (b) in 1967. Large amounts of channel shifting are evident. The letter 'M' on photo (a) and the arrow indicate a migrating channel. Channels A and B are discussed in the text. The numbers indicate features explained in Fig. 14. The letter 'L' indicates an area of linguoid bars. (Photo (a) is 161)

(a)



(b)



continuing to migrate in this direction, because in 1975 it was deepest on its south side and the sand flat here had an eroded margin during the period 1973 - 1975. The sediments deposited during this type of channel migration are partly channel-fill and partly sand flat material (Chapter VI).

Observations made before and after the flood of 1975 suggested another mechanism for channel shifting. Before the flood, the channel marked A (north end of the lower photo) was 1.5 to 2 m deep, discharging a large proportion of the water and sediment passing this cross-section. After the flood, this channel had aggraded, becoming about 1 m deep. Much of the flow that it had carried previously had diverted to the channel marked B. This mechanism of vertical aggradation and diversion of flow elsewhere in the system is similar to the mechanism proposed by Chien (1961) in the Lower Yellow River.

The aggradation of this major channel did not involve the formation of large bars; rather, the channel aggraded mainly by the deposition of sediment transported in the form of dunes. This implies that relatively thick accumulations of channel sediments are formed, which could be preserved in some circumstances.

THE STRATIFICATION OF CHANNEL DEPOSITS

Introduction

The stratification of the channel deposits must be inferred because the deep channels could not be box cored, and only a very limited amount of exposure of these sediments is present in the river banks. These inferences concerning the stratification are made mainly by consideration of the bedform types observed in the channels and the sedimentary structures generated by these. The grain sizes observed in the channels are also considered here.

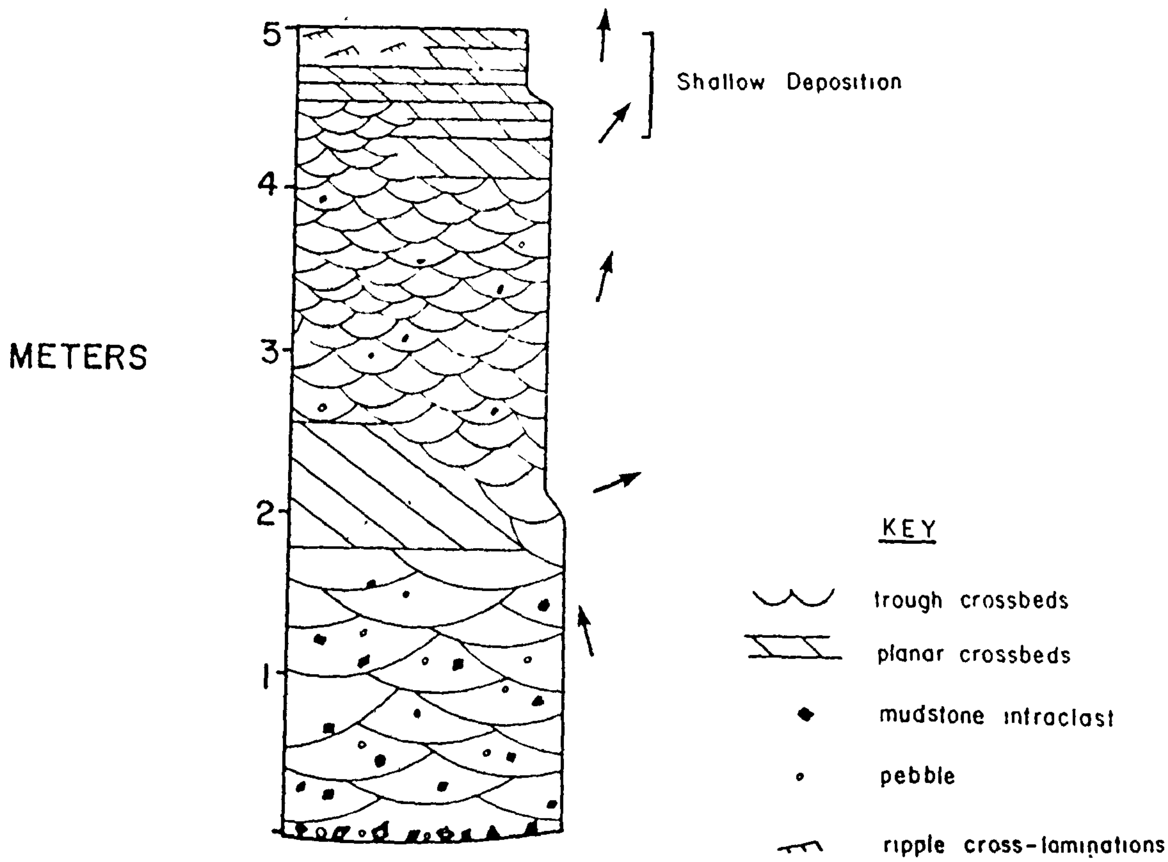
The Channel Deposits

This section will consider the stratification deposited by an aggrading channel which starts as one of the major channels in the system, and ends by being a very shallow minor channel. This type of aggradation occurs only within the channel, with no development of sand flats. This is one end member of a spectrum of sedimentary sequences ranging from this purely channel deposit to a sequence with a complete development of a sand flat complex (Chapter VI).

The top .75 metres of channel fill is topographically high, and differs little from the deposits of other aggraded areas in the system, such as low sand flats. The distinction between this topmost channel fill and shallow water, bar top deposition (Chapter VI) is somewhat arbitrary, but a complete section will be illustrated (Fig. 39).

FIG. 39. An idealized section through the channel deposits. The upper part of the section labelled "shallow deposition" refers to the deposits of minor channels.

CHANNEL DEPOSITS



The base of a newly-established major channel is erosional in nature. During a flood, switching of a large amount of discharge to a different channel will cause that channel to erode its bed to accommodate the increased flow. This has been observed by Coleman (1969). This erosional state lasts only a very short period of time until the stage begins to fall. On the base of the channel, a lag deposit forms which is composed mainly of mudstone intraclasts and ice rafted boulders present in the eroded sediment (Chapter VII).

Immediately above this lag deposit, the channel fill will consist of medium sand with large trough crossbeds deposited by large dunes active at high flow stages (Chapter IV). Scattered pebbles up to 5 cm in diameter are present in these deposits. Pebbles of this size were observed on the beds of major channels after the recession of the 1975 flood. During this high flow stage, much undercutting of the muddy vertical accretion deposits of islands and floodplains occurred. Many mudstone intraclasts of highly variable sizes were deposited in the channels at that time. Therefore, the basal channel fill of large trough crossbeds would also have scattered intraclasts throughout.

The deposits of flood events are preferentially preserved in the channels (Chapter IV) because of the larger sizes and deeper scour troughs of the bedforms during high stages. Because flood stage velocities are high, even in the shallower parts of the system, there is only a little fining-upward tendency in the channel deposits.

In other parts of the channels, the large bars discussed previously in this chapter are present. Some of these may develop into sand flats (Chapter VI), but many simply grow downstream, depositing sets of planar tabular crossbeds associated with the trough crossbeds of the other channel deposits. Because of the modes of formation of these bars (Chapter III), and their diagonal nature (this chapter), the paleocurrent directions of planar crossbed sets would be at high angles to those of the trough crossbeds.

As the channel aggrades and flow is diverted elsewhere in the braided system, flow depths and velocities decline, and the dunes present in it are smaller in size. The deposits of this part of the channel will be slightly finer, with fewer pebbles and intraclasts present. As the channel aggrades farther and is almost completely filled, the dunes give way at many times to sand waves and ripples. This is similar to the type of sedimentation which occurs on the tops of the sand flats. Many small planar crossbed sets and ripple cross-laminations are formed. These types of deposits could be regarded as occurring above the real channel fill, but because minor channels give rise to them in many cases, they are included here as part of the channel fill. In Fig. 39, these are indicated as "Shallow Deposition".

CHAPTER VI

THE SAND FLATS

INTRODUCTION

The large complex braid bars in the South Saskatchewan River are here termed sand flats. They are very important in the river because of their abundance and size. They form an integral part of the large-scale organization of the river (Chapter III), and have a great effect on its hydraulic geometry (Chapter II). Because of the size and relative stability (discussed later in this chapter) of these geomorphic elements, their deposits are potentially preservable in the geologic record. About 30 sand flats of various sizes and morphologies have been mapped in detail (13 are presented in Appendix 5) and many more have been studied by surface and aerial reconnaissance.

The fundamental reasons for the formation of sand flats are not understood. The answer to this question is essentially the same as the answer to the question, "Why is this river braided?". The causes of braiding were discussed in Chapter I, where the factors which promote braiding were considered. The most important of these in the case of the South Saskatchewan River are: 1) a heavy load of sand; 2) erodible banks; 3) rapid, high magnitude discharge fluctuations.

Nowhere in the literature is there a complete description of sand flats or an hypothesis concerning their origin; however, illustrations of similar features have been published. Collinson (1970, Fig. 3-8) showed a number of large sand flats in the Tana River which have similar sizes and morphologies to those of the South Saskatchewan, but these were not described in the text. Coleman (1969, Figs. 20, 21) has illustrated and briefly described depositional braid bars in the Brahmaputra River, which are similar in morphology to the sand flats under study here. However, those in the Brahmaputra are much larger than those in the South Saskatchewan. They may be proportionally larger because of the large size of the river in which they are developed.

GENERAL DESCRIPTION OF SAND FLATS

Sand flats are highly variable in all aspects, but particularly in size. They range in length from 50 m to approximately 2 km, and in width from 30 to 450 m. They stand from 1 to 5 m above the level of the channel beds around them (Fig. 3).

The larger sand flats, those longer than about 100 m, show a great deal of variety in shape because they have persisted for several years, through many flood events. Their original forms have been greatly modified by erosion and accretion. They are elongated parallel to the river (Fig. 38), but this is the only generality which can be made about their shapes.

The smaller sand flats show a much more restricted range of morphologies. These are interpretable in terms of the modes of origin of the small sand flats. Because of the importance of the processes of initiation of sand flats, these morphologies will be described in detail in a separate section.

The sand flats are exposed when the discharge is below 230 m^3/sec (Chapter II) and when the river is not frozen (Chapter VII). After the recession of a flood, the surfaces of the sand flats are covered by bedforms, most commonly ripples and sand waves, or bars of varying heights (Fig. 40). The upper 10 to 20 cm of the sand flats dry out after several weeks of exposure and are commonly eroded by the wind. Aeolian sand dunes up to 40 cm in amplitude are developed in a few places on the surfaces of sand flats, but are more common where sand is blown into an area of vegetation on banks and islands (Fig. 41). The sand flats themselves are almost devoid of vegetation; however, in some localities, small colonies of bushes may establish themselves.

In many places, the sand flats are traversed by minor drainage channels which are floored by sand waves and ripples (Appendix 5, Fig. 13). These channels occupy depressions between topographically high parts of the sand flat and, in most cases, are non-erosional. They are simply low areas of the sand flat where flow may proceed.

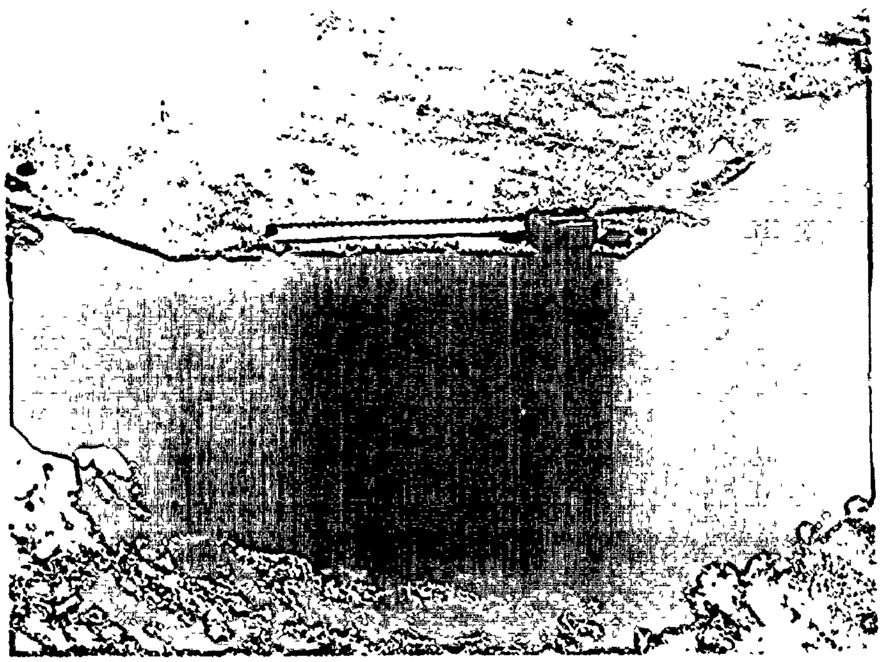


FIG. 40. A planar crossbed set overlain by parallel laminations. These bar and plane bed deposits were laid down during the flood of 1975. The tape is extended 30 cm.

FIG. 41. A large aeolian dune slipface building into a vegetated island. The slipface is approximately 2.5 m high.

Irregular shaped scours, deep holes and occasional large cobbles occur on the surfaces of sand flats. These are attributable to the effects of ice and its breakup in the spring (Chapter VII).

MORPHOLOGIES AND ORIGINS OF SMALL SAND FLATS

Many sand flats on the scale of 100 m or less in length are believed to be relatively newly-formed. Several reasons exist for this opinion· 1) some small sand flats were observed developing during the period 1973-1975; 2) small sand flats present during this time were not identifiable on a set of 1971 air photos; 3) many small sand flats were observed to be destroyed during the flood of 1975. If new sand flats of this size were not coming into existence, the destructive action of high flood stages would have eliminated them from the river.

Because the smaller sand flats have been initiated relatively recently, they reflect the conditions and processes which formed them much better than do the larger sand flats. Therefore, the study of the smaller ones is the best method available to attempt to gain an understanding of the mechanism of formation of the sand flats.

Small sand flats form in areas where the flow widens, or where an apparent widening such as a bend in the flow occurs (Chapter IV). They develop in the channels, in spaces between larger geomorphic elements such as older sand flats, islands, and banks. As will be shown below, their modes of origin and morphologies are markedly affected by the presence of these older deposits.

The small sand flats have a relatively restricted range of morphologies. They can be considered in terms of three end members: a) symmetric; b) asymmetric; c) side flats; each of which are illustrated in Fig. 42. They represent ideal cases, with continuous gradation among all the types.

(a) Symmetric Flats

As shown in Fig. 42, in its simplest form this type consists of an exposed high area of sand with a bifurcated downstream margin. This irregular margin is a slipface, but all others slope gently off into the channels. The slipface comprises part of a bar front which extends across the channels on either side of the sand flat.

This type of sand flat forms in the middles of channels where the flow expands laterally. In Fig. 43, successive stages in the formation of this type of sand flat are shown. In part (a), a curving bar is illustrated spanning the channel where it broadens. As the stage falls in (b), a portion of the bar top near the centre of its downstream margin has become emergent. This emergent area acts as the body of the sand flat, and is here termed a "nucleus". In part (c), the remainder of the bar front is shown building

FIG. 42. An illustration showing the three end member types of small sand flats.

Part (a) shows a small symmetric flat, with the two horns extending downstream from the main body of the flat.

Part (b) shows a triangular small asymmetric flat.

Part (c) shows a small side flat developed alongside a bank.

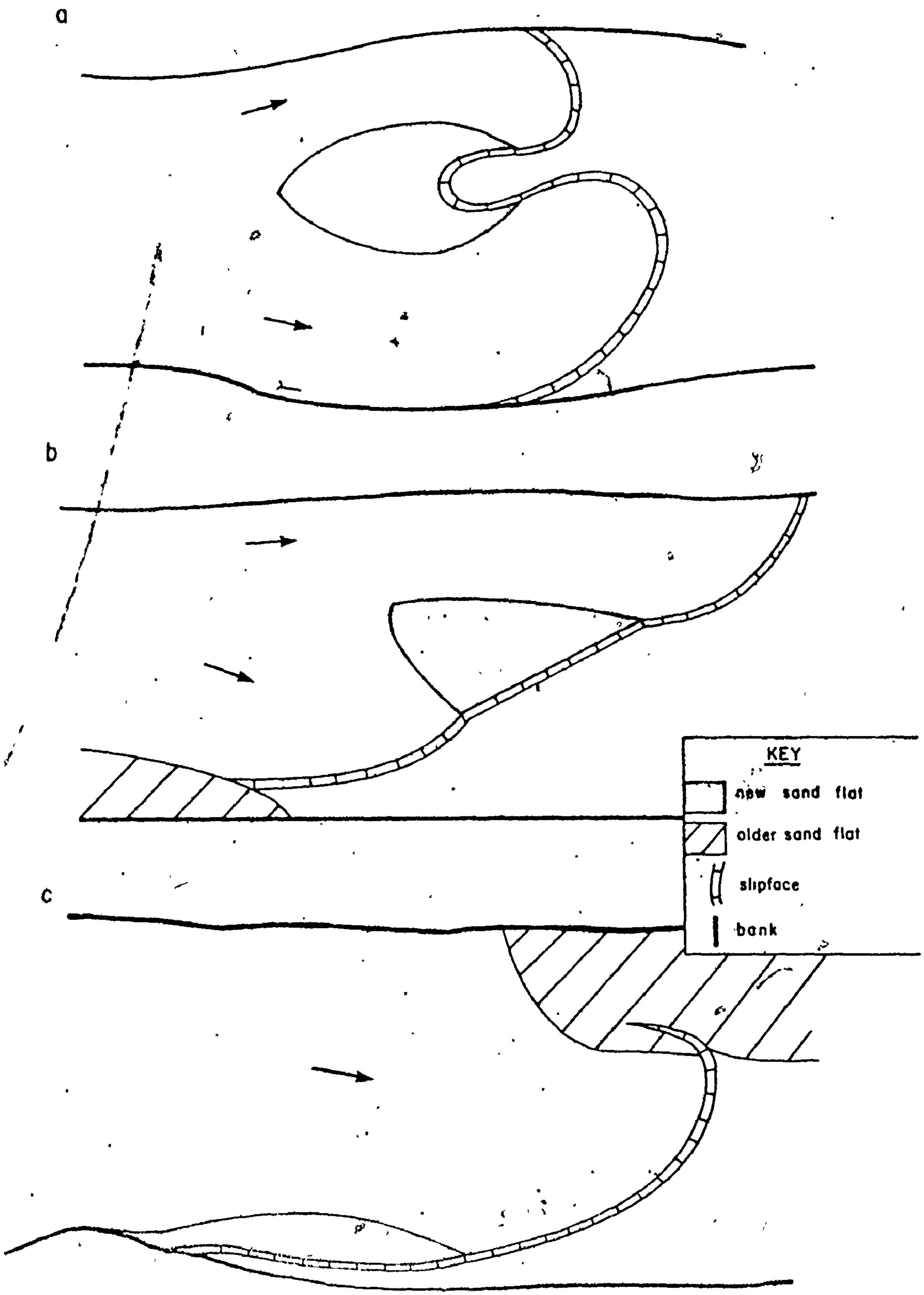
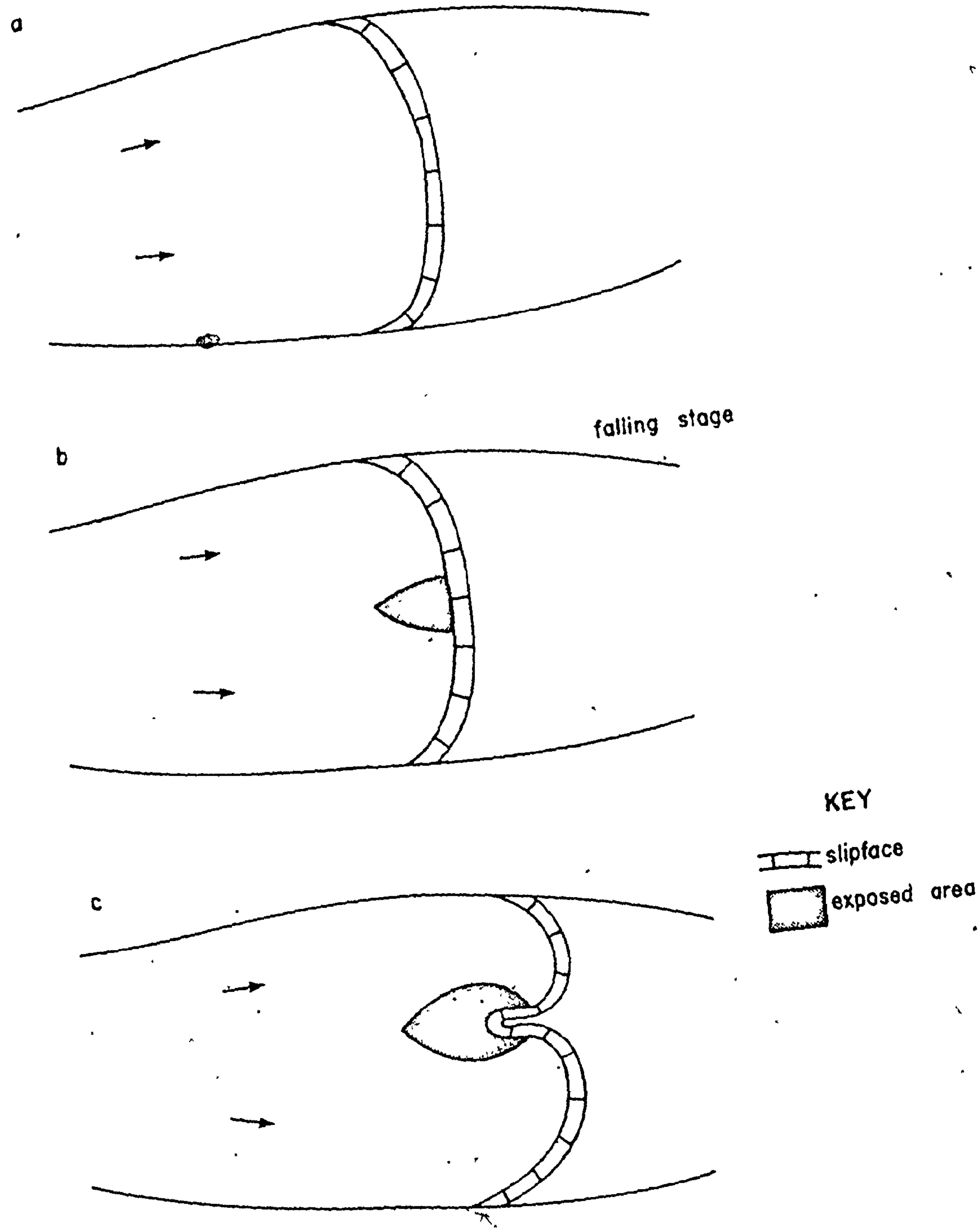

a
b
c
KEY
new sand flat
older sand flat
slipface
bank

FIG. 43. The formation of a small symmetric sand flat from a cross-channel bar.

THE FORMATION OF SYMMETRIC FLATS



forward, around the nucleus on both sides. The submerged parts of the bar are covered by ripples and sand waves or dunes. The two emergent portions of the bar front which extend downstream from the nucleus are termed "horns". They commonly build toward the central axis of the sand flat because of lateral flow expansion (Chapter IV) around the downstream end of the sand flat.

This sequence of events has been observed directly in one place. By consideration of morphologies observed on air photos, the sequence of events is also inferred to have taken place at many other localities in the river. An illustration of this type of sand flat is given in Fig. 44.

The reason for one portion of the bar top being slightly higher than the remainder is not clear. It has been observed that this high area or nucleus forms close to the centre of the bar where the bar is symmetric. This may be caused by the pattern of lateral flow expansion over the top of the bar. Smith (1971, Fig. 7) has illustrated contours of stream power over the top of a small bar. The maximum stream power occurs in the centre of the upstream part of the bar top, and the minimum at the centre of the downstream margin. The difference in the sediment transporting capacity of the flow in these two areas may explain why the central part of the downstream margin builds slightly higher than the rest of the bar top. Once an initial difference in height is created, it is increased as the stage falls and the flow is more con-

ed la

FIG. 44. A small symmetric sand flat formed on a lobate bar front. A second nucleus has become emergent near this.

In a few cases, the control on the location of formation of the nucleus is more obvious. Where a part of a bar front builds forward onto older, topographically higher deposits, the bar top in this area becomes slightly higher. The reason for this is not clearly understood.

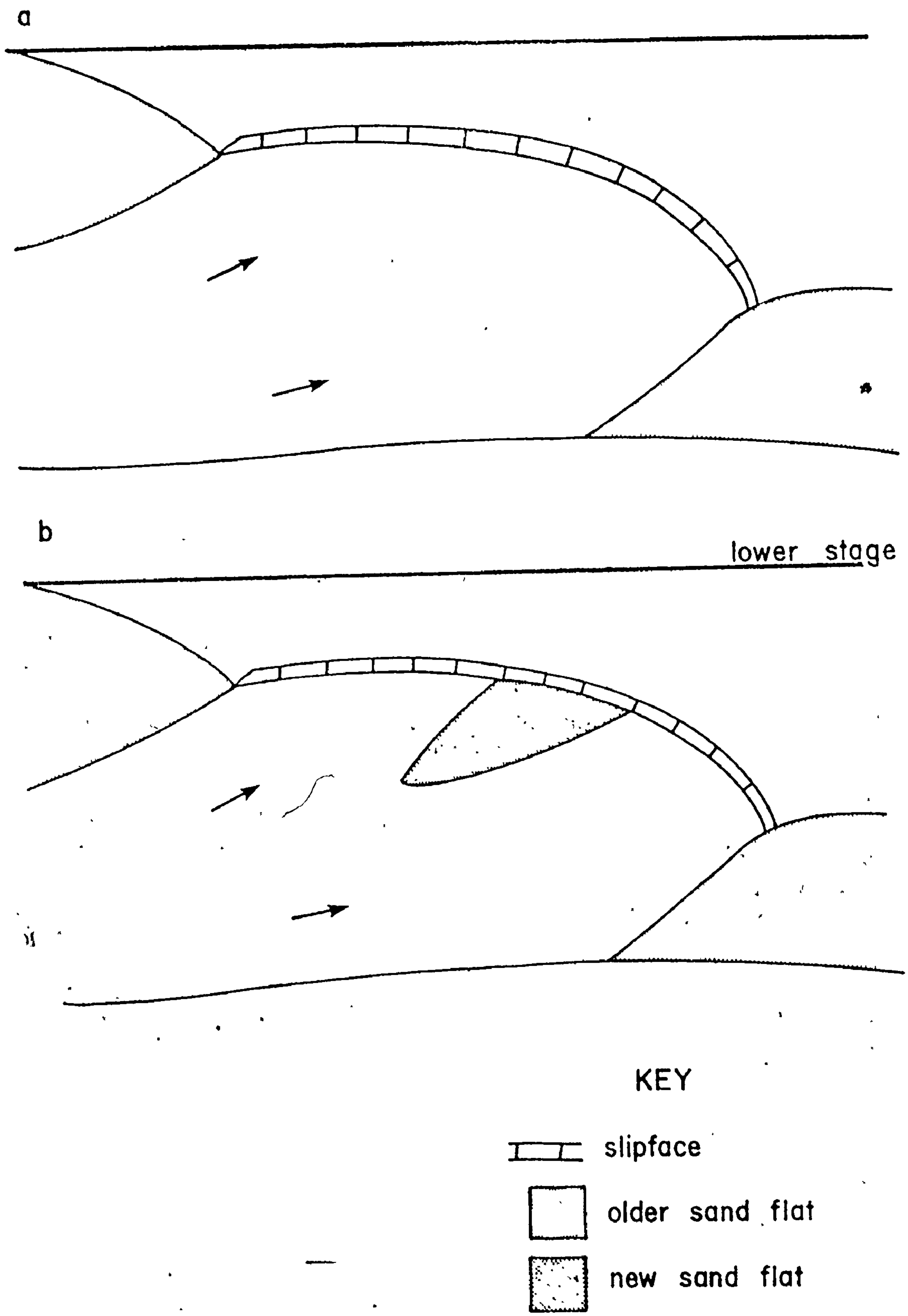
This type of sand flat has a veneer of ripples and sand waves in most cases, but is composed mainly of the bar deposits. Trenching shows that these sand flats are made up mainly of one set of planar crossbeds with a complex paleo-current pattern. This will be discussed extensively in a later section.

(b) Asymmetric Flats

This type of sand flat is very simple, consisting of a triangular-shaped, topographically high area developed on a diagonal bar (Fig. 42). The downstream margin of the sand flat forms part of the bar front which may extend across one or both of the channels.

The sequence of development of this type of sand flat is shown in Fig. 45. In part (a), a diagonal bar has formed where the flow spills laterally (Chapters III, IV) because of the control exerted by the pre-existing topography. In part (b), as the stage falls, a portion of the bar top at the downstream margin has become emergent. This is a roughly triangular part of the bar which has been built slightly higher than the remainder of the bar. Because of the diagonal nature of the bar, lateral flow expansion into its lee is

FIG. 45. The formation of a small asymmetric sand flat from a diagonal cross-channel bar.


a
b
lower stage
KEY
slipface
older sand flat
new sand flat

poorly developed. As a result, horns do not form. Asymmetric flats remain as triangular wedges of sediment in mid-channel (Fig. 46).

This type of sand flat again has a veneer of small bedforms, commonly ripples and sand waves. The underlying foundation, however, is observed to be the planar crossbed set deposited by the bar front. This crossbed set shows a paleocurrent direction at high angles to the river direction.

(c) Side Flats

This type of sand flat is developed alongside a stable bank of an island or floodplain. Each of these sand flats consists of a wedge of sediment in the form of a bar which has advanced towards the bank (Fig. 42). They greatly resemble the scroll bars which form the point bars of some meandering rivers (Sundborg, 1956; Jackson, 1976).

Side flats form in the lees of small points or other protuberances of the banks. In these areas, lateral flow expansion around the point causes the deposition of a bar (Chapter IV) with a slipface heading inward towards the bank (Fig. 47). This creates a quiet water slough behind the bar front. The bar reaches its maximum height near its upstream end, and slopes off downstream until it passes into the channel. The bar may extend completely across the channel, linking to another sand flat or island. Side flats, therefore, resemble one-half of a symmetric flat. One is illustrated in Fig. 48.

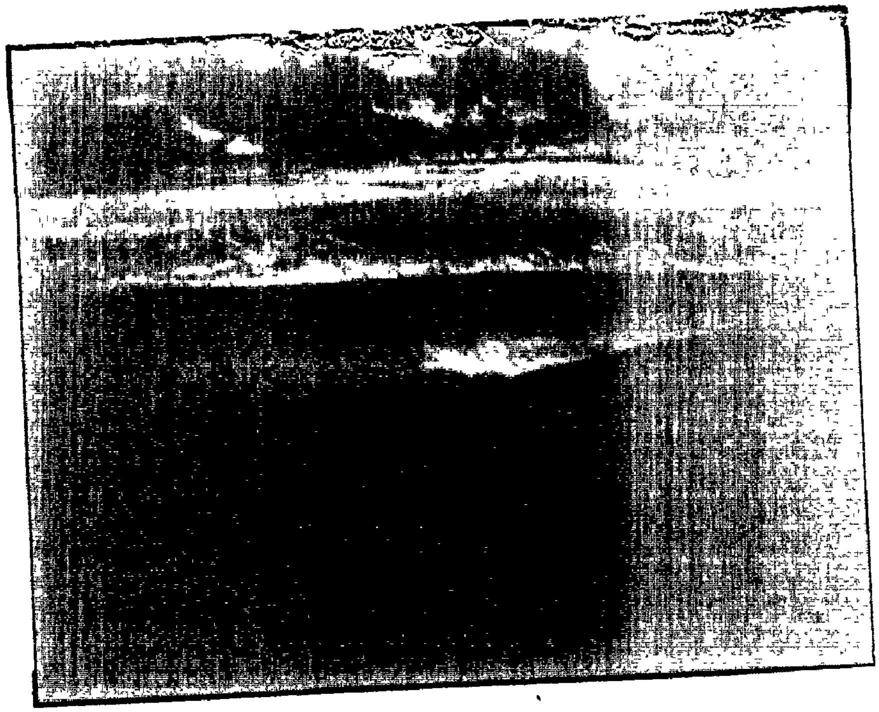
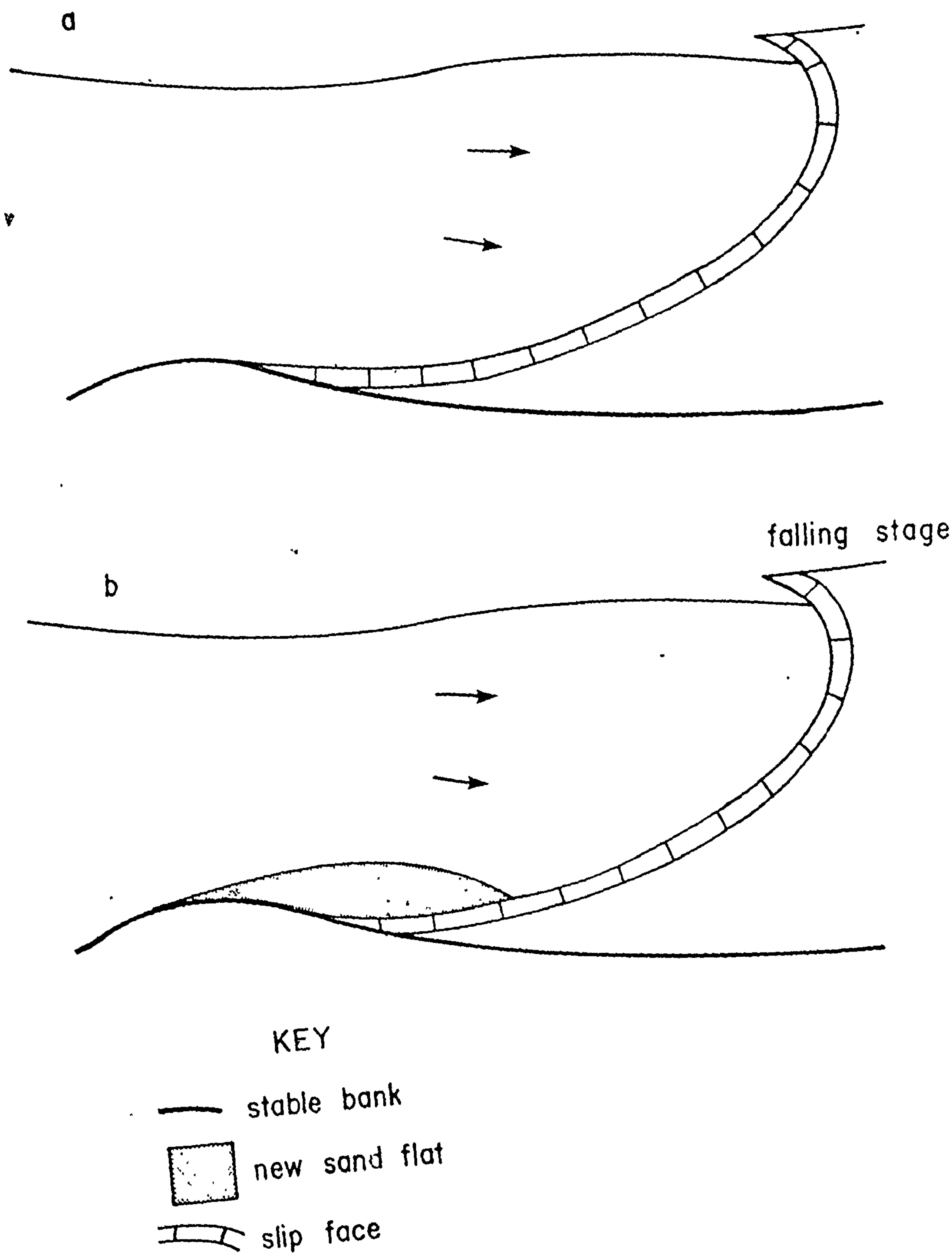


FIG. 46. A small asymmetric sand flat developed near an island. The sharp-edged margin of the flat is a slipface facing diagonally across the river. Downstream is to the right. A large cross-channel bar is building from the other direction, the bottom of the photograph.

FIG. 47. The formation of a small side flat from a cross-channel bar in the lee of a point on the bank.

THE FORMATION OF SIDE FLATS



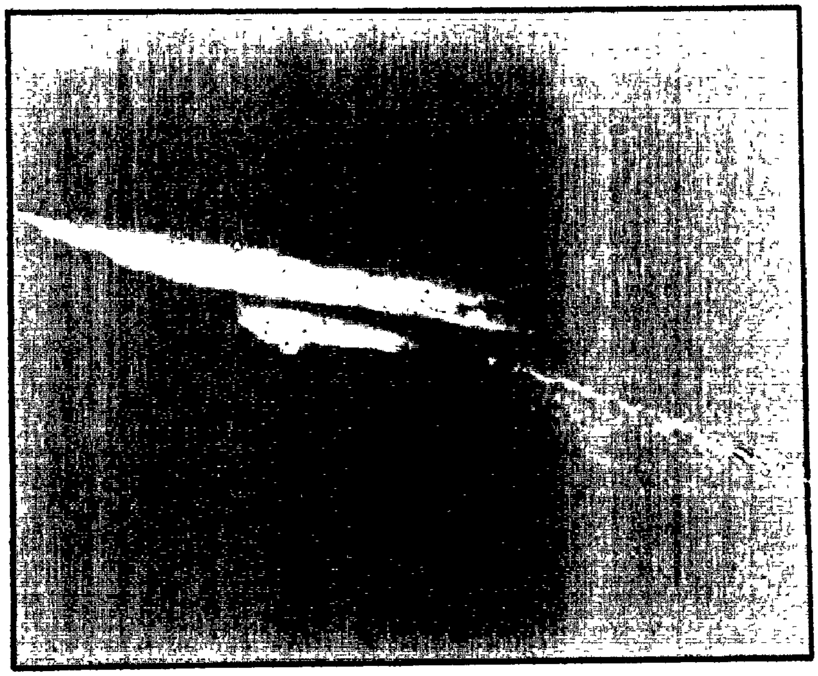


FIG. 48. A small side flat developed downstream from a point. The inner margin is a slipface heading inward towards the bank, creating a quiet slough. The bar comprising the sand flat extends downstream, connecting with the sand flat shown in Fig. 53. Flow is to the right.

Trenching shows that side flats are similar to the other types in that they have a veneer of small bedforms over the planar crossbed set of the bar. This set of crossbeds is observed to show a very high paleocurrent divergence from the local river direction.

These three different morphologies of newly-formed sand flats all originate from large bars in the river. In Chapter III, the organization of the river was discussed, with particular attention paid to the formation of large cross-channel bars. Where parts of these bars become emergent, new sand flats are formed, as discussed above. The large cross-channel bars are the main loci of formation of new sand flats in the river.

The change from a cross-channel bar to a bar with one or more emergent nuclei to a bar system including one or more sand flats is a gradual and reversible process. The small sand flats are prone to destruction during floods, when they are almost as deeply submerged as the remainder of the bar system.

Most of the sand flats seen in the river are larger and more complex (Figs. 36, 38) than the ones described above. The small sand flats, however, illustrate the basic mechanisms of the primary accumulation of sand which may eventually form a mature sand flat. The processes by which the smaller sand flats are converted to the larger, more complex forms will be discussed below.

THE PROCESSES OF MODIFICATION

The processes which will be described below can happen to a sand flat of any type or size. The processes of accretion and linking of sand flats are very important because they are the mechanisms by which the small sand flats just discussed become the larger, more common forms. Some of these processes were observed occurring on many sand flats for long periods of time (a, b, c, d), but others were inferred from observations made on a small number of sand flats before and after a flood (e, f).

The six processes are: a) lateral bar accretion; b) upstream bar accretion; c) vertical accretion; d) lee-side sedimentation; e) linking of sand flats; f) erosional modification.

(a) Lateral Bar Accretion

In Chapter IV, bar formation was discussed in terms of flow expansion. In places where the flow curves around the side or downstream end of a sand flat, it expands laterally, forming a bar. These bars always face inward towards the sand flat and accrete to it (Fig. 49). They also lengthen downstream as the flow is diverted farther around them on the falling stage. This was documented in several places by repeatedly staking the slipface of one of these bars.

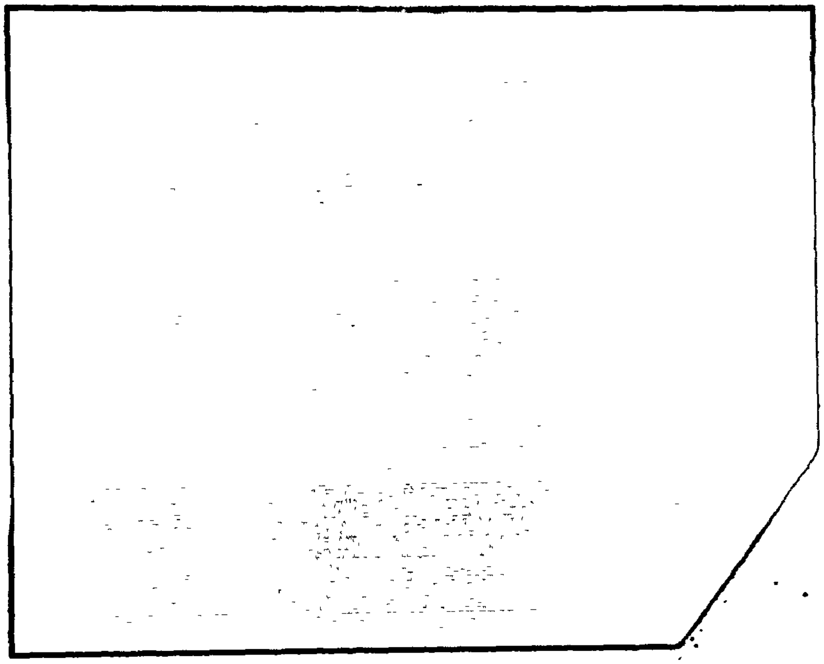


FIG. 49. An oblique air photo of two lateral accretion bars building onto a sand flat in the lee of an island. This illustrates that lateral flow expansion is important in the formation of these bars. They are covered by sand waves. See also Figs. 27 and 50.

This process is illustrated by the maps of sand flats presented in Appendix 5, specifically Nos. 4, 5, 6, 10 and 11. This process is essentially the same mechanism which forms small side flats (discussed above) and scroll bars in meandering streams. Accretion of this type occurs mainly at moderate to low stages because very high stage flow over the sand flats precludes the necessary flow expansion. The accretion of a bar to the side of a sand flat creates a quiet, backwater slough between the slipface and the sand flat where mud and organic debris commonly accumulate.

Where flow expansion occurs from both sides around the downstream end of a sand flat, two bars are formed which face one another (Appendix 5, Nos. 5, 10), similar to the horns on a small symmetric sand flat. The bars discussed here differ from the horns in that they are secondary, and may have formed a long time after the main body of the sand flat. They may taper off downstream or they may form cross-channel bars. Trenching shows that these accretionary bars are composed of small to moderate (less than 40 cm thick) sets of planar crossbeds which have paleocurrent directions at high angles to the river direction.

Lateral bar accretion is very common in the river (Figs. 13, 38) and appears to be one of the most important mechanisms of growth of the sand flats.

(b) Upstream Bar Accretion

This process is similar to the one described previously in that a bar accretes onto a sand flat; however, it differs in that the bar advances directly downstream onto the sand flat (Fig. 50). The process is illustrated in Appendix 5, Nos. 8, 13. The reason why a bar should advance up a slope is not entirely clear, but it appears that the process occurs at high stage. Bars which form upstream of sand flats in areas of widening channels are driven up onto the backs of sand flats. As the stage falls, they are left exposed, accreted to the sand flat. Most of the exposed bar rests on pre-existing sand flat deposit, but some is probably underlain by channel deposits.

Upstream accretion wedges are common in the system. However, the process only occurs at high stage, and it is believed, happens so infrequently to any one sand flat that little upstream growth occurs, relative to the amount of lateral and downstream bar accretion.

This process causes the deposition of planar crossbed sets on the upstream ends of sand flats. These crossbeds, observed in many trenches, do not show as much paleocurrent deviation from the local river direction as do those deposited by lateral bar accretion.

FIG. 50. A sand flat which has undergone rapid accretion. A large upstream accretion bar was built onto the sand flat in the flood of 1975. Major amounts of vertical accretion have also taken place. Lateral accretion is also evident on the side of the sand flat. Flow is to the top right.

(c) Vertical Accretion

Sediment can be transported onto the sand flats only during moderate to high stage. Although this condition may prevail only a small fraction of the time, substantial amounts of sediment accumulate on the sand flats because of high sediment transport rates during floods.

The greatest amounts of vertical accretion result from the advancement of large bars over the surfaces of the sand flats. This process is indicated on maps 1, 2, 3, 6, 7, 8 and 13 in Appendix 5. Lesser amounts of accretion occur because of the migration of ripples, sand waves, dunes and plane bed on the sand flats. Of these, the lower flow regime bedforms are present at moderate stages, and the plane bed at very high stages. In many cases, the crossbeds deposited by the large bars appear to have replaced previously existing lower stage deposits. On several sand flats, the thickness of the vertical accretion deposits after the 1975 flood (about 1 metre) was much greater than the topographic change. Therefore, the pre-existing deposits must have been partly eroded before the deposition of the flood deposits. These consisted of large bars depositing planar crossbeds, capped in some cases by as much as 40 cm of parallel lamination (Fig. 40). Because of this selective preservation of flood deposits, much of the deposits of the sand flats is believed to consist of planar crossbeds.

If a flood stage is very high, the flow sweeps directly downstream over the sand flats. In this case, the vertical accretion deposits have paleocurrent directions very close to the local river direction. This was the result of the 1975 flood (peak flow of 1812 m^3/sec); the planar crossbeds and parting lineation on the parallel lamination headed directly downstream.

However, if the flood stage is not so high, the bars building over the sand flats are markedly affected by the older topography of the sand flats. As the flow begins to wane, parts of the bars building over old high areas cease to migrate and the remainder of the bar fronts build around them. This is analogous to the formation of small symmetric flats. This is shown in map 3, Appendix 5, where a younger bar front has built over a pre-existing sand flat. This map was made after the recession of the 1974 flood (peak flow 850 m^3/sec). This bar was not built into deep water or directly onto channel deposits. Vertical accretion bars of this morphology were common after the 1974 flood. It is important to distinguish the true development of a new sand flat from this type of reworking of an old one, even though the resulting morphologies may be superficially similar.

The planar crossbeds in this case were observed to have a higher paleocurrent dispersion than ones deposited by a very high flood.

The major exception to all this is the case of side flats, where the banks constitute an obstruction to flow at all stages. In this case, deposits of all stages have paleocurrent directions which are observed to head towards the bank.

(d) Lee-side Sedimentation

Because sand flats are obstructions to low and moderate flows, they create protected, low velocity areas in their lees. During moderate flows, sand is transported over the top of a sand flat, and is trapped at the downstream margin, usually in the slipface. At lower stages, when the sand flat is emergent, fine sands and silts are transported around the sides of the sand flats and deposited in the area of quiet water (Appendix 5, Nos. 2, 7, 11). Where two downstream-pointing horns are present on a sand flat, the area between them receives only silt and mud sedimentation (Appendix 5, No. 3).

This process probably accounts for a large amount of the growth of many sand flats. Moderate and high stage fore-set deposits alone have been observed to cause a sand flat to extend several metres downstream in only a few days.

(e) Joining of Sand Flats

To create very large sand flats (see map at back of thesis), either small sand flats must accrete a great deal, or several sand flats must be joined into a single entity. A process was observed in two places which, in each case, caused the linking of a pair of smaller sand flats into a larger one. This process was inferred to have happened by comparing configurations and morphologies of the sand flats in the local area before and after the flood of 1975. Because no formal mapping had been carried out in these two areas, only reconnaissance, it is not possible to present maps to show the changes.

The process involved the building of a large bar across the downstream end of a small channel separating two sand flats (Chapter IV). This bar built up at high stage until it was at the same topographic elevation as the two sand flats. When the stage fell, the channel was completely blocked and the two sand flats were joined.

This mechanism may be the way in which very large sand flats form. Because the formation of these very large ones probably takes years, this has not been directly observed, and the proposed mechanism is speculative. Enough minor channels could be blocked to create the wide expanses of sand flats which are now observed at many places in the river.

(f) Erosional Modification

In many cases, the morphology of a sand flat is markedly changed by erosion, where a channel migrates laterally against it. This process was discussed partly in Chapter V in the section on channel shifting, and is illustrated in Fig. 38. In most cases, a curving erosional margin is created by a channel cutting laterally into a sand flat (Fig. 51).

FIG. 51. The sand flat in the foreground has been eroded on both sides. On the near side, small erosion faces can be seen at the vegetated area. On the far side, a typical curving erosional margin is present. Flow curves around to the right.

Erosional trimming of the tops of some sand flats also occurs at moderate to high stages when the flow can sweep over them. The upstream ends and sides of sand flats are the areas most prone to suffer this, because they are most exposed to the oncoming flow. The depth of erosion is highly variable. A series of stakes driven into selected sand flats showed that the depth of erosion over a 9-month period (September, 1974 - May, 1975) was up to .5 m, but was highly variable. Much of this removal may have occurred during the winter or at breakup in the spring (see Chapter VII).

These six types of processes are the most important ways in which sand flats are modified. Lateral bar accretion, vertical accretion, and joining of sand flats are probably the more quantitatively important constructional processes. These are the means by which small sand flats grow and change into the larger forms which will be discussed in the next section.

LARGER SAND FLATS

As a result of the interaction between the processes of modification and pre-existing sand flats, most sand flats differ markedly from the small sand flats discussed previously. This is shown by inspection of most air photos (Figs. 36, 38) and the maps of Appendix 5. In Fig. 52(a), one typical sand flat is illustrated, with topographic profiles across it

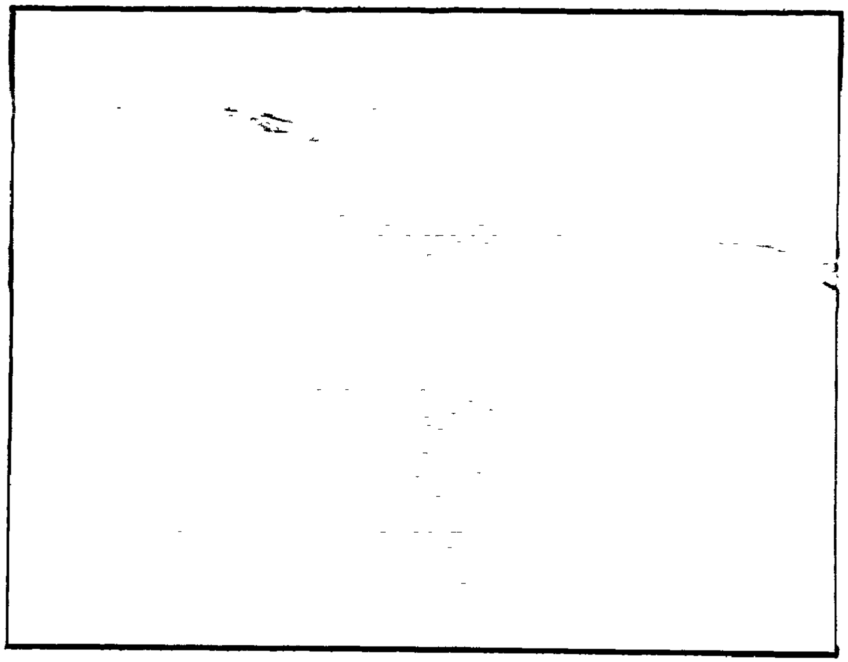
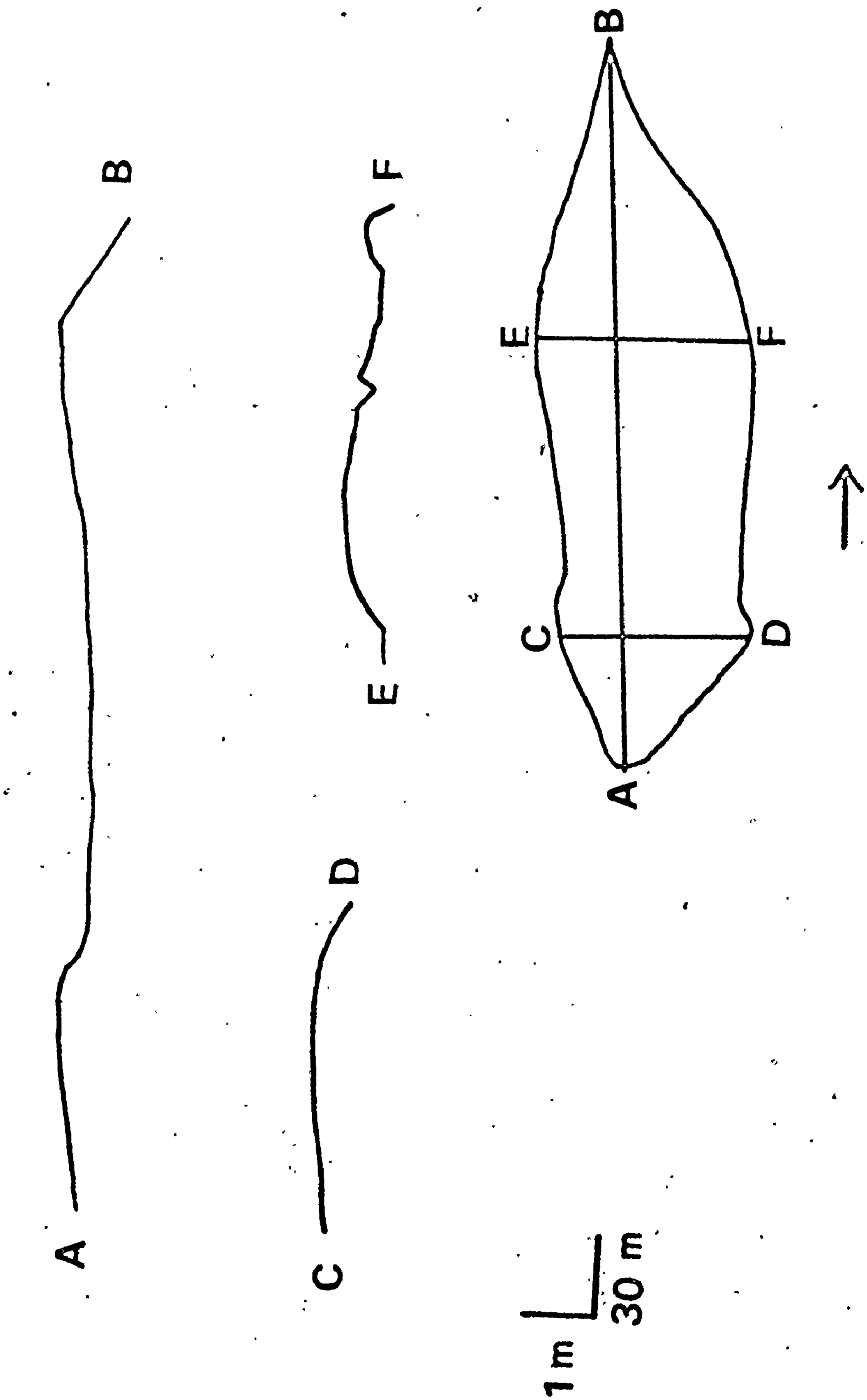


FIG. 52(a). A typical sand flat. Flow is to the right.

FIG. 52(b). Topographic profiles across the sand flat in (a).


A
B
C
D
E
F
A
B
C
D
E
F
1 m
30 m

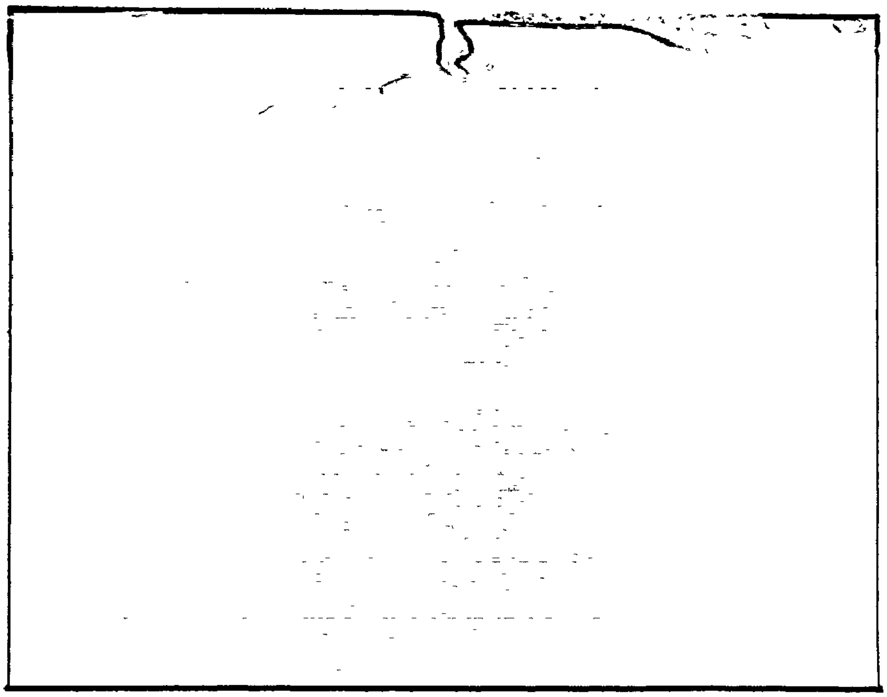


FIG. 52(c). A large side flat with several lateral accretion bars, an aeolian ridge and a deep slough at the bank side. It is linked by cross-channel bar to the sand flat at the head of the island. Flow is to the lower left.

shown in (b) of that figure. This sand flat has undergone upstream and vertical accretion, as shown by the bars developed on it. It is covered in most areas by sand waves and ripples. It is linked by cross-channel bars to other sand flats at both its upstream and downstream ends.

Unlike the small sand flats discussed previously, no easily interpreted modes of origin exist for these larger, more complex sand flats. The small sand flats represent simple depositional forms which are essentially unmodified after their formation, what Smith (1974) referred to as "unit" bars. The larger sand flats, however, may have very complex histories. For example, the sand flat illustrated in Fig. 52(a) is developed on the site of an older sand flat. It is known from air photos and mapping of the area (downstream part, map 13, Appendix 5) that a sand flat had existed in this location for at least four years previously. This older sand flat was extensively modified during the flood of 1975 with the sand flat shown in Fig. 52(a) resulting from part of it. This sand flat, therefore, has more than the deposits of a single bar within it. It possesses the deeper deposits of the older sand flat, which was itself very complex. The details of stratification will be considered in the last section of this chapter.

Another larger sand flat is shown in Fig. 52(c). This sand flat is developed along the side of the river bank, and therefore is a type of side flat. Air photos show that a sand flat of similar morphology has existed here since 1967. The present morphology of the sand flat results from the reworking of the older sand flat in the flood of 1975. The sand flat slopes upward away from the channel until it reaches an older, higher aeolian ridge which is partly vegetated. At the bank side, a deep backwater slough exists, which is bordered by a slipface heading inwards towards the bank. At the outer margin of the sand flat, a lateral accretion bar has been driven onto the flat. This bar is also heading inward towards the bank. Except for the aeolian ridge, the entire surface of the sand flat is covered by sand waves and ripples. Cross-channel bars link it to other sand flats at both its upstream and downstream margins.

This sand flat will again have a substructure which it inherited from older ones developed here. The presence of the bank is apparently an effective control on the morphology of a sand flat developed at this locality. Because the older sand flats shown on air photos had essentially the same morphologies, the paleocurrent directions of the major cross-bed sets within them will all be heading inward towards the bank.

SAND FLAT COMPLEXES

Sand flat complexes have been described briefly in Chapter III (Fig. 15), and illustrated on the map at the back of this thesis. A map of a typical sand flat complex is given in Appendix 5, No. 13. They may consist of very large single sand flats or several sand flats separated by channels which are less than 1.5 m deep. Two sand flat complexes typical of these types are illustrated in Fig. 15 and Fig. 53.

The sand flat complex shown in Fig. 53 is the largest single sand flat in the river, extending about 2 km in length. It incorporates several islands within itself and is crossed in a few places by shallow drainage channels. These are dry at low to moderate river stages, and are susceptible to infilling at flood stages. The upstream part of this sand flat probably has survived since 1960, when a sand flat existed in the same location. This part of the sand flat has been subjected to many floods since 1960 (Chapter II). In the flood of 1975, this sand flat received rapid vertical accretion, with many large bars being driven up onto its surface.

The sand flat complex illustrated in Fig. 15 consists of a number of individual sand flats along with several small channels. Many of the sand flats are linked by cross-channel bars. The sand flats have highly variable morphologies, reflecting the large amounts of modification they have experienced. Each sand flat in the complex may have evolved separately and then linked up with the others, but it is more likely that each influenced the other. In some cases, this type of complex may be the result of dissection of larger sand flats by shallow channels. The morphology is not

of fo

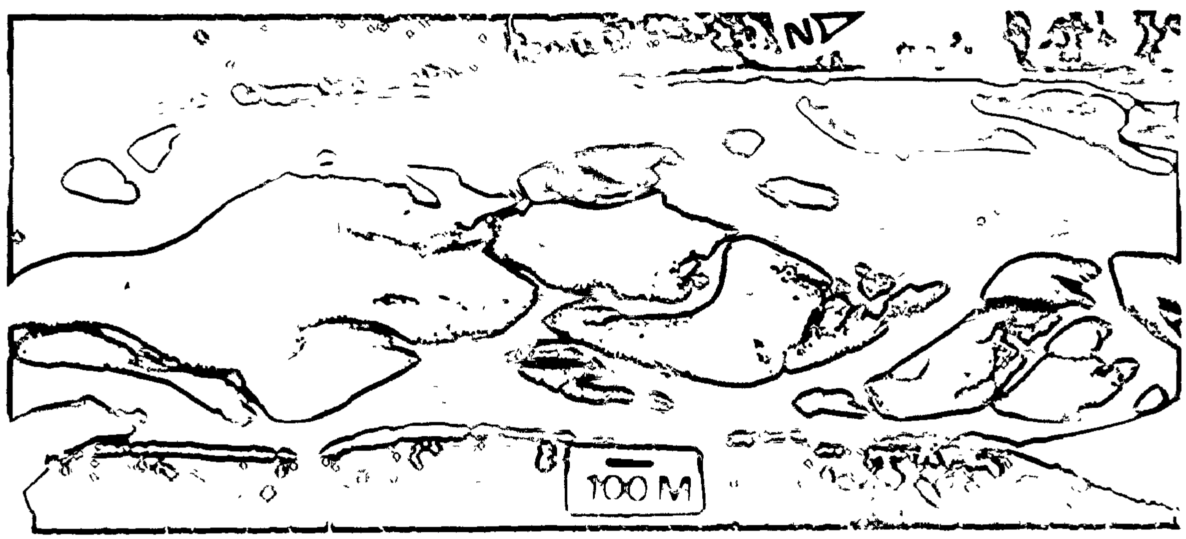


FIG. 53. The largest sand flat in the river. It incorporates three islands within itself. Only very minor channels cross this sand flat. (Photo 155)

The deposits of a sand flat complex, therefore, may bear little relation to the surface features. The stratification will be considered in a following section.

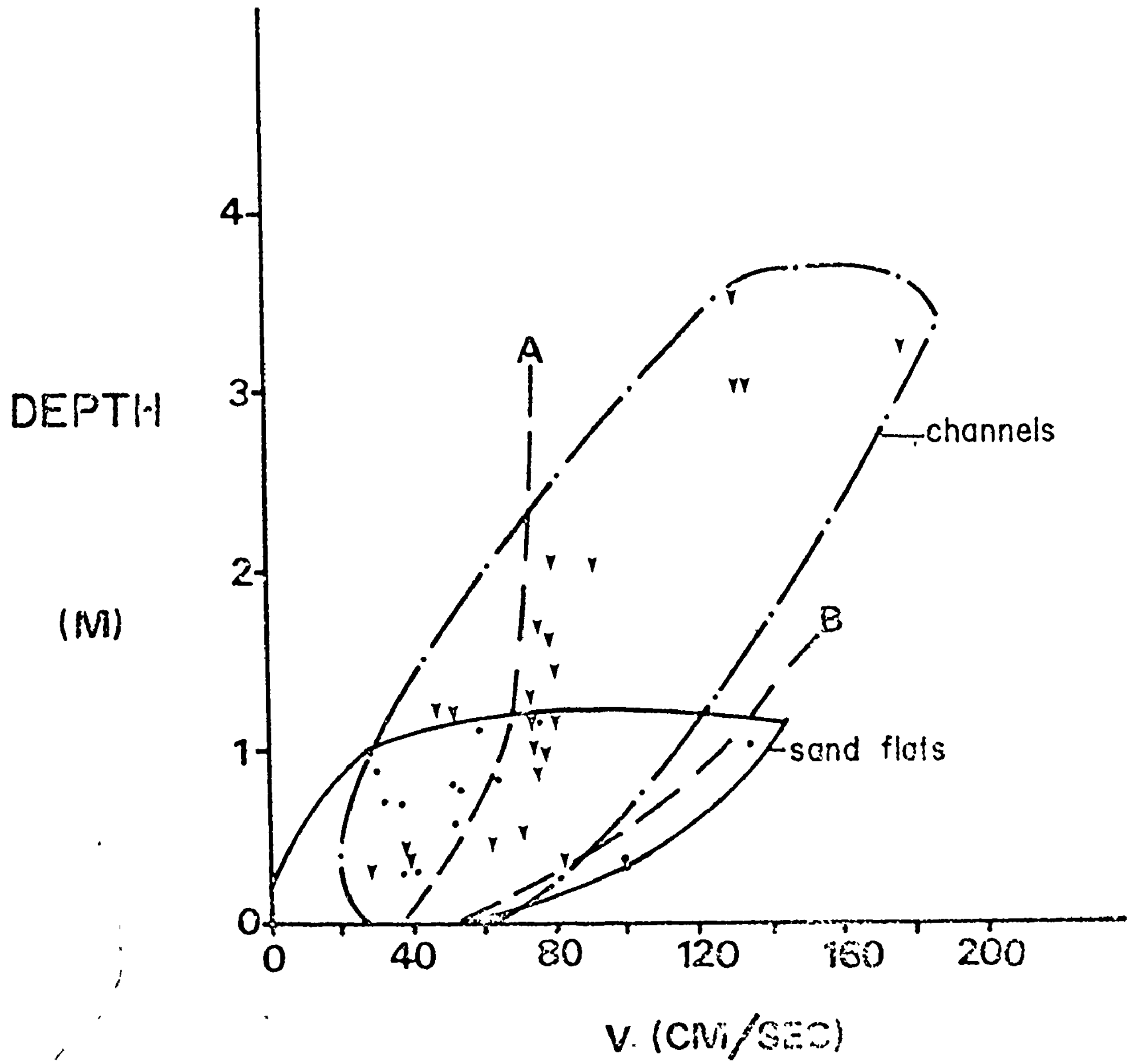
The reasons for the formation of these very large geomorphic elements are not understood. The processes involved in their formation must involve a build-up of sand and the exclusion of major channels. They do not occur in any specific relationships with islands or banks, so they do not seem to be controlled to any great extent by these stable elements. Their development, therefore, may be controlled entirely by the long-term pattern of major channel migration.

HYDRAULIC COMPARISON OF SAND FLATS AND CHANNELS

In Fig. 54, the ranges of depth-velocity conditions observed in the channels and on the sand flats are illustrated. Also on this diagram, the stability fields of sand waves, dunes and plane bed (after Boothroyd and Hubbard, 1974) are shown. Some of the points are estimates of mean velocity from the observed surface velocities, and one is an estimate of velocity from the bedform type and the depth. The points represent all observed flow stages. It should be emphasized that this diagram represents only an estimate of the conditions.

The diagram shows that there is considerable overlap in the conditions of shallow channels and sand flats. This overlap occurs mainly in the sand wave field, but partly in the dune field. Both minor channels and sand flats may have

FIG. 54. A depth-velocity plot of the channels and sand flats. This diagram attempts only to show the range of variation in the conditions present in each. Some of the points are estimates from the bedforms present and the observed depths. Others are estimates from surface velocity measurements made in the channels at flood stage. Line A separates conditions which produce sand waves (left) from dunes (right), and Line B separates dunes (left) from plane bed (right). The dots represent measurements and estimates made on sand flats and triangles represent those made in channels.


DEPTH
(M)
4
3
2
1
0
A
B
channels
sand flats
0
40
80
120
160
200
V. (CM/SEC)

both these types of bedforms developed on them. However, dunes are more common in small channels, and sand waves are more common on sand flats. Channels have much deeper flows than sand flats, but the maximum velocities are not much different. The difference in depth, however, keeps the channel flows in the dune stability field, whereas the fastest flows over the sand flats reach the plane bed field.

If the plotted points proportionally represented all conditions in the two sub-environments, it is believed that sand flats and channels would be more distinct. Sand flats would concentrate in the sand wave field, and channels mainly in the dune field. However, sampling problems preclude this approach.

THE STRATIFICATION OF SAND FLATS

In the last two sections, the diversity and complexity of larger sand flats and sand flat complexes have been discussed. Because most of these large sand bodies are developed on pre-existing deposits, the internal stratification is not directly predictable from the surface morphology. Only in the cases of the small sand flats discussed earlier can the stratification be deduced from the surface morphology.

Because of this uncertainty and the inherent variability of sand flats, only general patterns of stratification can be presented. Also, a limited amount of data is available because (1) deep trenching was impossible due to the high water table, and (2) no systematic trenching plan could be followed because of the size and variability of sand flats. Locally, significant deviations may occur, but these cannot be discussed because of the large numbers of possibilities.

The stratification sequences reported in this chapter are the result of integration of data from the following sources: 1) trenching to the water table on sand flats; 2) inferences from morphologies of small sand flats; 3) inferences and observations on the processes of modification of sand flats; 4) study of a bank section believed to be an older sand flat deposit (Appendix 2).

Extensive trenching on many different sand flats in August, 1973 and 1975 revealed that the higher deposits of sand flats consisted of moderate to large-sized planar crossbed sets covered by smaller structures such as shallow scour fills, ripple cross-lamination, small planar crossbed sets, and some small trough crossbeds. Most of these structures are attributable to shallow water deposition or ice action (Chapter VII) on the sand flats. The deeper structures of sand flats were investigated by trenching and box coring small, newly-formed sand flats, and by consideration of their morphologies. The stratification of larger sand flats and sand flat complexes were studied by observing and monitoring processes of modification of sand flats, along with trenching the results of these processes. Study of the deposits preserved in the banks of the river, particularly in one long section near Outlook (Appendix 2) helped tie all the stratification data and inferences into one coherent whole.

THE BANK SECTION (Appendix 2)

This bank showed sequences of sedimentary structures which resembled those seen in trenching the upper 50 cm of the sand flats, and those observed in box cores and inferred from processes and morphologies to exist below this. This bank is on the east side of the river, and has probably been preserved because of bridge construction near it. It extends almost 250 m downstream and stands 1.5 to 2 m high. The sections shown in Appendix 2 are separated by about 8 m each. Each section was tied into an arbitrary topographic datum, so they bear the correct topographic relationship to each other. They have been divided into three units (in most cases) and correlated with one another (Appendix 2).

The three major units are defined to be: 1) a basal unit of planar crossbed sets greater than 30 cm in thickness; 2) a middle unit of small planar and trough crossbed sets, irregular scour fillings, ripple cross-lamination and parallel lamination; 3) an upper unit of mixed sandy and muddy vertical accretion deposits. The two lower units are almost all sand and are believed to be sand flat deposits for the following reasons: 1) their resemblance to the deposits observed in 50 cm deep trenches on the sand flats; 2) the presence of stacked sets of planar crossbed sets at the bottom of the sequence; 3) presence of mud drapes in scours cut into the second unit; 4) most of the planar crossbeds have paleocurrent directions at high angles to the present river, heading inward towards the bank. This latter fact suggested that the bank was formed by a side flat.

The planar crossbeds in the basal unit commonly dip less than the angle of repose, and may be very asymptotic at the base. Reactivation structures are common within them. These probably represent the main body of the sand flat, the lateral and vertical bar accretion from one side onto lower sand flat deposits.

The second unit is very heterogeneous, representing deposition in shallow water on top of the sand flat, and modification of the top of the sand flat. The ripple cross-laminations, small planar crossbed sets, trough crossbed sets, and parallel lamination represent the deposition of sand in the forms of ripples, sand waves, dunes and plane bed respectively. The irregular scours are small erosional features cut into the top of the sand flat, many of which may be related to ice action (Chapter VII). Some of these are filled by well-sorted, faintly laminated sand which may have been blown in.

In profiles 24 - 26, the crossbed sets in unit 1 head out towards the channel. This may represent a subsidiary bar building out of the slough at the bank side. The unit of ripples at the bottom of sections 19 - 21 probably represents a small channel cutting across the sand flat, heading towards the slough at the bank.

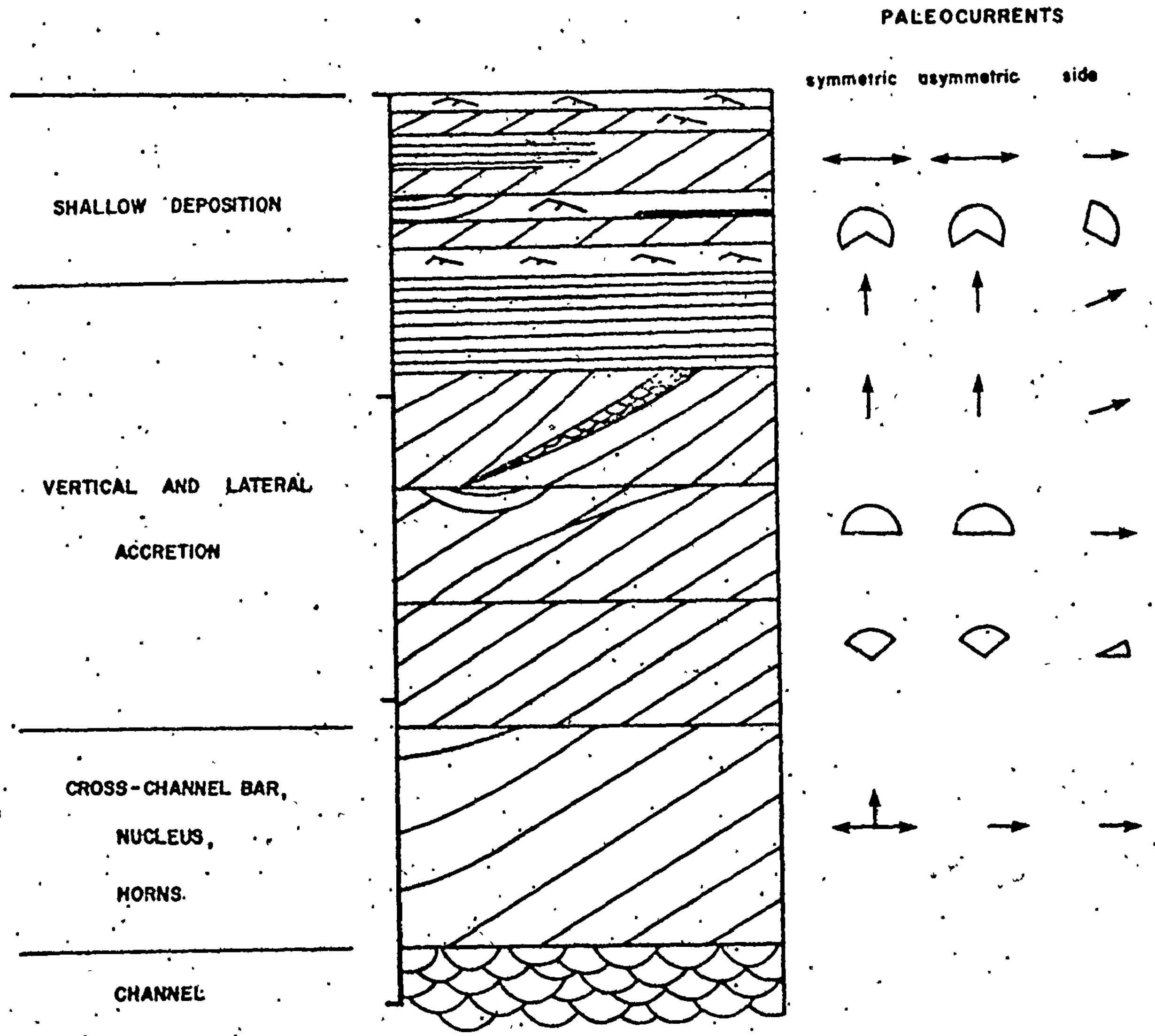
The data obtained from this bank section showed that the patterns of sedimentation, of side flats at least, are reflected in the preserved deposits. It is inferred that this link established between the processes of sedimentation on active side flats and the preserved deposits in the bank can be extended to mid-channel sand flats.

THE SEDIMENTARY SECTION

In spite of the variability among sand flats, enough similarities exist to allow some generalizations to be made about their stratification. All newly-formed sand flats originate from cross-channel bars: therefore, the lowest unit of a sand flat should be a planar crossbed set developed on top of trough crossbeds of a channel deposit. The different morphologies of the small sand flats will be reflected in the paleocurrent pattern of this crossbed set. For each of the three morphologies, the paleocurrent variation is shown beside the general section through a sand flat shown in Fig. 55. The symmetric flat has a lower crossbed set which has tri-modal direction, representing the main body of the flat and the two horns. The other two types have lower units with uni-modal directions at high angles to the river direction.

FIG. 55. An hypothetical section through a fully developed sand flat. The paleocurrent patterns for the different types of sand flats are shown on the right. The downriver direction is represented by a vertical arrow. The arcs represent possible ranges of paleocurrent directions.

SAND FLAT STRATIFICATION



Most of the processes which result in the growth, linking and modification of sand flats involve bars. Therefore, most of the deposit above the basal set will consist of planar crossbeds. The thicknesses of the sets should decline upwards because of the increased topographic height of the sand flat and the likelihood of truncation by later sets.

The lower two sets of the middle unit represent lateral and upstream bar accretion onto the sand flat. The paleocurrents of these sets in mid-channel types of sand flats show wide spreads in directions because of the diversity of processes involved. The paleocurrents of these sets in the side flats show unimodal directions similar to the basal sets. This occurs because accretion can only take place from one side due to the presence of the bank.

The upper planar crossbed set and the upper flow regime parallel laminations represent vertical accretion during flood stages. These types of structures were observed to comprise the main deposits of the 1975 flood. In the mid-channel flats, the paleocurrent directions of these deposits may be unimodal and parallel to the river direction because the flood flow was high, and swept directly over the sand flats. If the planar crossbeds are the deposits of a lesser flood, however, they will show a greater paleocurrent dispersion. On side flats, the paleocurrent directions of these deposits head at a high angle to the river direction because the bank provides a constraint at all stages.

The scour, reactivation structure, and ripple accretion zone illustrated as occurring in the crossbeds of this middle section may occur anywhere. They are irregularities and are impossible to predict.

In the upper part of the section, the deposits of shallow water prevail. These consist of ripple cross-lamination, small planar crossbed sets deposited by sand waves, and a small amount of plane bed. In addition, there is one planar set deposited by a lateral accretion bar. It has a paleocurrent pattern of high dispersion. With the exception of the bar cross-stratification, these shallow deposits resemble the deposits at the top of the channel sequence (Fig. 39).

Not illustrated here are many irregularities of sedimentation which occur locally on the tops of sand flats. Some of these are described briefly below.

1. Deep, circular, isolated pools are sometimes present on the tops of sand flats. These likely form because of scour pockets at irregularities in bar fronts, but are maintained by scour under the ice during the winter (see Chapter VII).

2. Many minor structures are generated by waves striking the tops and margins of sand flats. Small beaches, with concentrations of magnetite and garnet, wave ripples, and 10 cm high hooked spits are common.

3. Small aeolian dunes in places are present on the sand flats which may be preserved (this chapter).

4. Other minor structures generated by ice (Chapter VII), animals or rain.

CHAPTER VII

WINTER EFFECTS

INTRODUCTION

Of the world's 21 major river systems (Coleman, 1969), eight are frozen more than 100 days a year (U.S. Navy Hydrographic Office, 1946). In spite of this, little is known about the effects of river ice on sedimentary processes or deposits. Very few studies have been done on frozen rivers, partly because of the difficulties in working in winter conditions.

The South Saskatchewan River is completely ice-covered from early November to mid-April most years (Water Survey of Canada, 1965-1971). This ice cover, and its breakup in the spring, might be expected to have significant effects on the system. Because little work has been done on ice-covered rivers, the nature of these effects could not be predicted. Therefore, a visit was made in April, 1975, to observe the river prior to and during breakup.

As was discussed in Chapter II, the Gardiner Dam has altered the discharge regime of the river during the winter months. Before the dam, during the months of December through March, the average discharge was about 100 m^3/sec; since completion of the dam, the average discharge has been about 300 m^3/sec. This increase in discharge under the ice may be the most important artificially imposed change in the river regime. Throughout this chapter, consideration will be given to the possibility that this has modified the observed processes.

THE RIVER IN WINTER

As has been stated above, the entire river system is covered by a layer of ice during the winter months. This ice cover shows great variability in structure, composition and thickness in different parts of the river.

Over the channels, the ice is commonly a homogeneous grey mass up to 50 cm thick, with no visible ice crystals. Over some major channels, however, the ice is made up of frozen-in ice blocks, many of which are oriented vertically. This indicates that a minor breakup occurred, forming the ice blocks, which were then frozen into a solid mass. The timing of this event, whether at freeze-up or later in the winter, is unknown. The ice cover over some minor channels is composed of alternating layers of ice and water. Up to four separate layers of water were observed at a single locality.

On the sand flats, the most common type of ice is made up of two distinct layers. The top layer (up to 50 cm thick) is composed only of vertically oriented prismatic ice crystals which average 15 cm in length. The lower layer is homogeneous grey ice much like that reported from the channels. The total thickness of the ice on the sand flats has been observed to be as much as 75 cm. In many places, thin, irregular patches of sand are present on the ice surface over the sand flats. The patches of sand may be rippled, indicating that flow over the ice occurred, at least locally.

Along the margins of the sand flats, cracks up to 5 cm wide penetrate the entire thickness of the ice. These cracks parallel the margins of the sand flats where they begin to slope off into the channels. The cracks are attributed to falling stage which caused lowering of the ice in the channels. Because the ice cover on the sand flats is supported by sediment, the ice at the margins of the flats is forced to crack to accommodate the bending of the once-flat sheet.

Small holes up to 20 cm in diameter are present along the margins of some channels. These are believed to be air holes kept free of ice by beavers and muskrats. On the ice surface beside some of these holes, small accumulations of sand have been built up. Sand in suspension was observed being carried onto the ice surface through some of these holes. Probing the channel bed through these revealed that the bottom sediment is not frozen, and in some cases is rippled.

By chopping through the ice cover on a sand flat, it was determined that the sediment is frozen to a depth of at least 15 cm. It is believed that the surfaces of all the sand flats are frozen most of the winter under the ice cover. This is important because it implies that the sand flats are essentially immobilized during the winter months, with only small modifications to their margins possible. This may account, in part, for the relatively slow changes in sand flat position and morphology (Chapter VI).

Because of the ice cover and the immobilized sand flats, the flow in the channels is constricted in all directions. Any increase in discharge during the winter months must be accommodated in the channels, probably resulting in relatively higher flow velocities. This effect may lead to deepening of the channels under the ice cover. However, this is speculative because no direct investigation of the hydraulics of the flow under the ice could be made.

The upper muddy layers of the floodplain and island banks are frozen to depths of 30 to 50 cm. The sandy layers underneath are not frozen and are subject to erosional attack if the flow impinges on them. Where the muddy layers are undercut in this manner, they develop large cracks parallel to the bank margins. Very large (5 m x 1 m) chunks of the muddy layers break free in this way, forming mud intraclasts.

In the pre-dam period, winter conditions in the river were likely to have been somewhat different. Discharges were so much lower that the sand flats were not covered by the flow during the winter months. Interstitial water in the sediments of the flats would have frozen very early in the winter and remained solid until spring. The sand flats were, therefore, even more static during the winter months of the pre-dam era. Because of the lower discharges, flow velocities in the channels were less, resulting in lower rates of sediment discharge and less scouring. Temporary thaws generated increases in discharge which caused higher flow velocities because of the constriction effect discussed above. This effect would have been present before, as well as after, dam construction.

In conclusion, it can be said that the construction of the dam has altered the system in winter to some extent, but most processes and their results are not markedly different.

SPRING BREAKUP

On some rivers, the ice breakup is a violent high energy effect. Collinson (1971b) has described the effects of this type of breakup on the sediments of the Tana River. Because of snowmelt in the nearby mountains at the same time as the river ice of the Tana is melting, breakup occurs during a rapid rise in stage. Considerable ice jamming and flotation of ice blocks onto bars takes place at this time. The grounding of these blocks generates linear drag marks and push ridges of sediment. Scouring around grounded blocks and local deposition of the eroded sand creates mounds and hollows of up to 1 m relief. Most of the documented effects are, therefore, a result of the rapid rise in stage and the high energy conditions which prevail during breakup.

In the South Saskatchewan River, discharges may be high in early April when breakup occurs. However, they are more commonly low to moderate, i.e., 150 to 300 m^3/sec (Chapter II). This results from the fact that little snow is present in the immediate vicinity to supply large volumes of water (see section on Climate, Chapter II), and the distant mountainous source region remains cold enough that snowmelt there does not add to the discharge at breakup. The major flood peak comes in June most years, long after breakup has occurred.

The Sequence of Events at Breakup

The style of breakup in the South Saskatchewan River reflects the low energy state of the flow while the ice cover is being removed. Much *in-situ* melting and softening of the ice occurs as daytime temperatures rise above 0°C. The largest channel opens up first, from upstream to downstream (Fig. 56). At the downstream end of the open water, an ice jam forms which moves intermittently downstream as the breakup proceeds. The open channel widens as large ice blocks (up to 5 x 10 m) break loose from the channel margins. The sizes

FIG. 56. The main channel opening from upstream to downstream with an ice jam at the end.

and shapes of these blocks are controlled by the cracks formed in the ice cover along the margins of the sand flats. Eventually the minor channels open in the same way that the major channels did, but with correspondingly smaller ice blocks and ice jams.

After the minor channels break up, the sand flats remain ice covered. On some topographically low sand flats, the ice is floated free or broken up by the flow, generating more ice blocks in the channels. Large floating ice blocks may ground and remain on these flats if the stage falls. On the majority of the sand flats, however, the main body of the ice melts in situ, with meltwater draining through holes and cracks, and flowing under the ice cover. During this period, the frozen sediment crust on the tops of the flats melts also. By the time all the ice has melted from the sand flats, normal summer processes are restored.

At the time of the visit, the nearby North Saskatchewan River was also breaking up. This river is similar in size to the South Saskatchewan, but is essentially unmodified by man. The breakup on this river resembled the one just described, with low flows and much in situ melting of the ice. This is an indication that the breakup observed on the South Saskatchewan was not markedly different from what it would have been if the river were not controlled.

In most years of the pre-dam era, the discharges of the river were low about the time breakup normally would have occurred. However, in a few years, high stages were recorded around the expected time of breakup. These probably caused breakup events much like that described by Collinson (1971b), with higher energy conditions prevailing. An occasional breakup of this type probably had little permanent effect on the river system. The presence of the dam has reduced the probability of this type of breakup occurring in future years. In this respect, the river regime has been altered, and the long-term effects of the change cannot be predicted. Few short-term effects are apparent at the present time, however.

THE EFFECTS OF BREAKUP ON THE SEDIMENTS

Not all of the events described above affect the river sediments to any great extent. The major events and processes which modify the sediments will be discussed below in greater detail.

(a) The Ice Jam

The main ice jam forms at the downstream end of the open water where floating ice blocks collide with the softened ice cover (Fig. 57). Some blocks crash into the jam and add to it on its upstream end or ride up on top of the blocks. Smaller blocks may dive under the jam with the downgoing flow and may surface within the jam. The water which descends

FIG. 57. Part of the ice jam shown in Fig. 56. Some of the blocks are 10 m in length. Flow is to the left.

under the jam upwells behind it, eventually melting the ice up to 200 m downstream. In some cases, a second very small jam may form at the end of this open reach. As more and more large blocks crash into the main jam and it is weakened by melting, it becomes unstable. After much jostling and rearrangement of ice blocks, it finally gives way and surges downstream at a walking pace to the end of the open water. By this method, the jam proceeds downstream and the channel opens.

The length of time the jam remains in one place is unpredictable. It was observed to be stationary for periods ranging from one-half hour to more than five hours. Because the flow is constricted beneath it, the jam can cause considerable scouring of the channel bed if it remains in one place long enough. At the locality where it was observed for more than five hours, sounding with a weighted line revealed a scour up to 1.5 m in depth. The ice jam, therefore, may have an important local effect on the sediments of the channels.

(b) Grounded and In Situ Ice Blocks

During breakup, floating ice blocks commonly ground on slightly submerged sand flats, then act as obstacles to the flow. In cases where blocks come to rest on irregular bases, or where two blocks are stranded very close to one another, flow constriction occurs with local scouring of the surface of the sand flat (Fig. 58). Some scours were observed

FIG. 58. A shallow scour in the lee of an ice block grounded on a sand flat. The rod is marked in 10 cm intervals.

being filled from the side by avalanching sediment which had been transported around the ice blocks. Where a block with a flat base grounds, deposition may result with a sand shadow being created. These erosional or depositional effects may also result from the flow being obstructed by a large in situ block.

Some ice blocks which have been partly melted underneath by the flow have bulbous knobs of ice extending downwards from their bases. In several places, these knobs were observed to penetrate the surfaces of the sand flats, creating steep-sided holes up to 15 cm deep (Fig. 59). It is unclear whether these knobs sank into the sediment because of the weight of the ice or were surrounded by sediment during local deposition. It is probable that both mechanisms are operative to some extent.

Although no direct link can be established, it is possible that some of the irregular scour-fill cross-stratification observed in the sand flats is caused by the presence of the ice blocks. The scour fills are commonly solitary, not occurring in great numbers cut into one another as trough cross-beds do. The scours may be filled by angle of repose foresets or by low angle cross-stratification. The basal scours of these sedimentary structures are on a similar scale and have similar shapes to the scours found in the lees of ice blocks. While other processes may form scours on the sand flats (Chapter VI), some of them probably result from the presence of stranded ice blocks.

FIG. 59. A knob on the bottom of an overturned ice block, and the imprint it left on the sediments.

(c) Floating Ice

Some evidence of floating ice in the system is preserved in the sediments. Gouging and grooving by ice blocks occurs in some shallow channels, but the linear depressions produced are very shallow and unlikely to be preserved more than a few days.

The floating ice leaves a more permanent record of itself by transporting very large clasts throughout the system. The ice frozen along the valley walls is in contact with pebbles, cobbles and boulders which were originally deposited as part of the Pleistocene till in the area. The river itself is incompetent to transport the larger clasts, but during breakup they are rafted throughout the system by floating ice blocks. As the ice blocks melt during transport, the clasts are dropped onto the sand bed. The majority of them are deposited in the channels, but some are carried onto topographically low sand flats. The association of moderately well-sorted sand with a few anomalously large clasts scattered throughout is a preservable result of the presence of the ice in the system.

OTHER EFFECTS OF THE ICE COVER

Several important effects on the sediments attributable to winter conditions were observed after breakup. It is believed, however, that these effects were not caused by breakup, but are the results of processes which were active when the river was completely ice-covered.

(a) Scouring on the Sand Flats

In the summer months; shallow channels which are floored by ripples, sand waves, and small (less than 15 cm) bars traverse the sand flats (Chapter VI). In a few of these channels, elongate pools up to 1 m deep were eroded during the winter months (Fig. 60). The pools cut under the ice are elongate, shallow and are restricted to the minor channels on the flats.

The origin of the scour pools is not definitely known because they could not be observed during their formation; however, it is believed that they result from scour localized by a break in the frozen sediment crust. Where a small original depression existed in the bottom of a minor channel, the frozen crust would be thinner. As flow proceeded down the minor channel during a small rise in stage, the thinner crust could be melted or eroded relatively easily. After the crust was breached, scouring and undercutting of the frozen crust would create an elongate depression in the minor channel. This would not be filled in because most of the surface of the sand flat was frozen, so no sediment was available for transport. A similar mechanism has been invoked for the origin of scour pits on frozen intertidal sand bars in the Bay of Fundy (Knight and Dalrymple, 1976).

FIG. 60. A series of pools developed along a minor channel on a sand flat. Each is marked by a hole in the ice cover. View is downstream.

(b) Disruption of the Tops of the Sand Flats

After breakup, the surfaces of most sand flats were relatively smooth with few large features, but some flats displayed areas where extreme disruption of the surface had occurred. Irregular hummocks and ridges of loose sediment and partly-filled scour pools were the main structures which caused up to 2.5 m of relief (Fig. 61).

The irregular hummocks and ridges were commonly composed of loose, structureless sand which was heaped up, sometimes on top of the ice to a depth of 30 cm, sometimes incorporating ice blocks within. Many of the largest hummocks did not contain any ice at the time of observation. A number of these together formed a ridge which paralleled a series of scour pools developed along a minor channel.

A few small mounds and ridges which did not contain ice were developed on the sediment surface. These appeared to be different in their mode of origin from the hummocks described above. These smaller forms were probably formed under the ice cover in hollows and caverns.

The scour pools were much like those discussed in the previous section, but here were partly infilled by ripples and bar fronts. The infilling may have taken place much later than the formation of the scour pools.

The mechanism responsible for the creation of the mounds and hollows and for ejecting up to 30 cm of sand on top of the ice could not be observed, but some inferences

FIG. 61. A highly disturbed area of a sand flat. Some of the irregular, structureless mounds of sediment contain ice blocks. View is upstream.

can be made about the processes involved. The smaller, well-laminated hummocks must be formed by an efficient hydraulic sorting process. Because this type of hummock forms under the ice in small hollows, it is believed that the mechanism involved the settling of suspended sediment from a flow up-welling through a hole in the ice. This would account for the domal structure and the well-developed lamination.

The structureless mounds which may incorporate ice blocks were probably formed by some other mechanism. In permafrost regions, pockets of water under high static pressures due to volume increase during freezing may burst upward through the ice cover carrying sediment. These are known as aufeiss (Church and Gilbert, 1975). It is believed that some form of fluid escape process similar to the formation of an aufeiss created the structureless hummocks of sediment. The fluid escape was probably generated below the sediment crust of the sand flats during a period of freezing when static pressures in the pore fluids would be at maximum. The upward escaping fluid carried large amounts of sediment in a fluidized state (Lowe, 1975).

CONCLUSIONS: THE IMPORTANCE OF WINTER EFFECTS IN THE RIVER

It can be concluded that winter processes in the river are subordinate in importance to those active during the summer period. No major amounts of sediment are laid down during the winter, and few major changes affect the sediments previously deposited. The effects of the ice cover and the spring breakup are not as important as those caused by a flood event (Chapters IV, V, VI). Summer processes also are sufficient to account for most of the observed deposits of the river system.

It is likely that the most important overall effect of winter conditions is the stabilization of the sand flats for four or five months each year, thus inhibiting major channel shifting. This is probably one of the most important controls on the rates of change of the shapes and locations of the sand flats in the system.

CHAPTER VIII

THE MODEL OF SEDIMENTATION

INTRODUCTION

The purpose of this chapter is to integrate the previously reported processes and stratification data into a coherent model of river sedimentation. In addition, some consideration will be made of longer term processes and their results.

The functions of a facies model have been discussed by Walker (in Harms et al, 1975). The most important aspects are: a model is a norm or standard which results from synthesis of many examples; it can be compared with other examples or used as a predictor in some cases. The model of sedimentation to be proposed is applicable at this time only to the South Saskatchewan River. Any wider application must come only after comparison with other sandy braided systems.

Most of the processes, morphologies, and stratification patterns reported earlier were observed in many places in the river. In these previous chapters, descriptions were necessarily generalized to keep these sections of this thesis to a manageable length. In this chapter, these already generalized portions will be combined without much further distillation into an overall model of braided river sedimentation.

VERTICAL RELATIONSHIPS

The most important processes and the resulting deposits in the river are illustrated in Fig. 62, a block diagram of the active environment and the preserved deposits.

The processes leading to the deposition of vertical sequences may be considered in terms of two end members, channel aggradation (Chapter V) and sand flat development (Chapter VI), between which a continuous spectrum exists. The sedimentary sequences which are inferred to result from each of these end members, as well as an intermediate case, are shown in Fig. 63, and are also marked on the block diagram (Fig. 62).

The processes of channel aggradation result in a sequence which consists mainly of trough crossbeds deposited by sinuous-crested dunes migrating in the channels. Because large flood-stage dunes have deep scour troughs, their deposits are preferentially preserved compared to lower stage smaller dunes (Chapter IV). As a channel aggrades, it carries progressively less discharge, with lower flow velocities and shallower depths resulting. The size of the dunes developed in these aggraded channels is less (Chapter IV), so the size of the corresponding trough crossbeds will be smaller. Many channels have cross-channel bars present in them which never develop into sand flats, and these can be considered part of the channel aggradation sequence. These bars are commonly oblique to the local river direction (Chapters III, IV), so

FIG. 62. A block diagram of part of the river, showing the active environment and the preserved deposits. The inset shows a vertical view of the same area. A, B and C indicate the locations of the three sections on Fig. 63, channel aggradation, an intermediate case, and sand flat development, respectively. The black unit within the block represents a localized mud deposit.

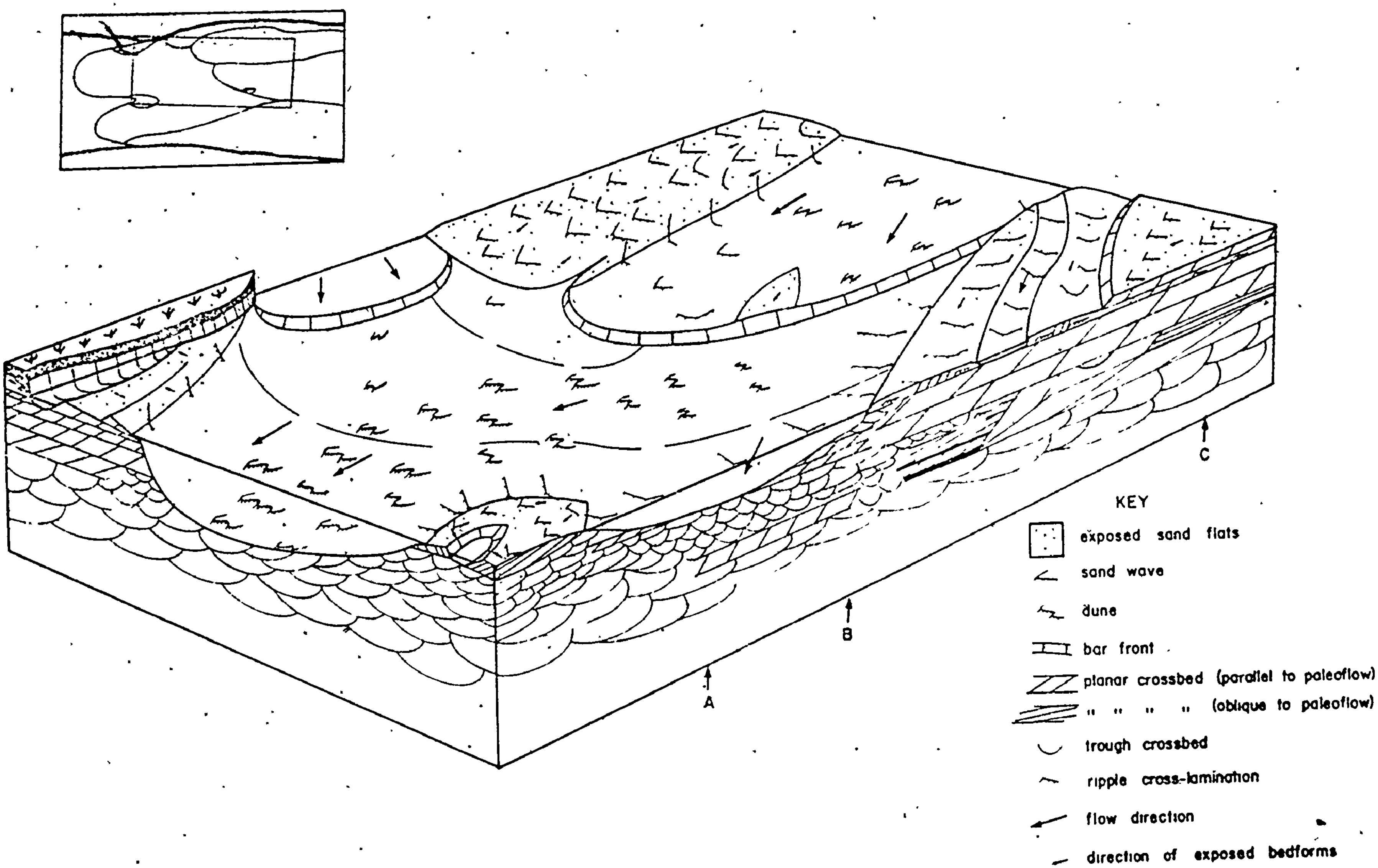
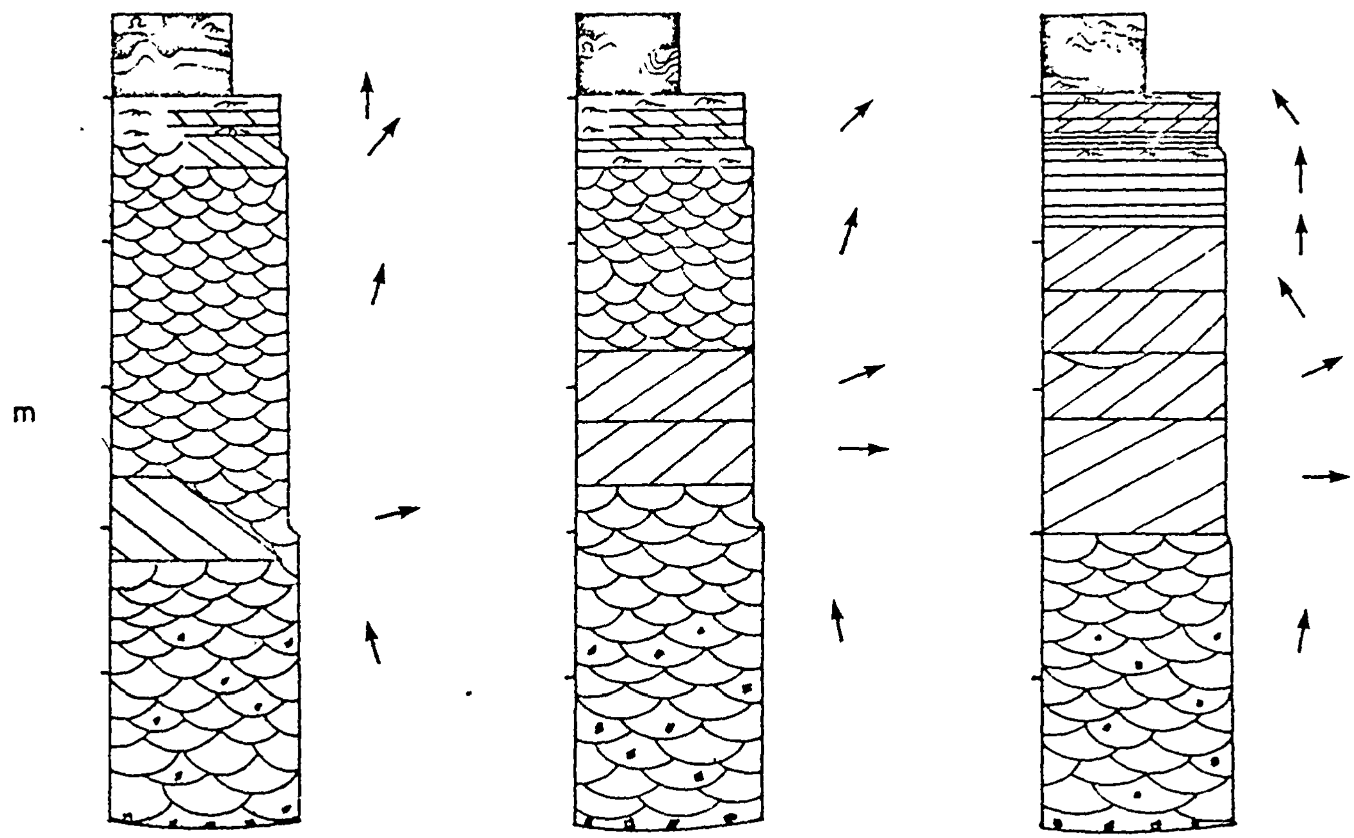

A
B
C
KEY
exposed sand flats
sand wave
dune
bar front
planar crossbed (parallel to paleoflow)
" " " (oblique to paleoflow)
trough crossbed
ripple cross-lamination
flow direction
direction of exposed bedforms

FIG. 63. The range of sedimentary sequences which could be produced by deposition in the river, two end members and one intermediate sequence. The paleocurrent arrows indicate only one of the possible paleocurrent patterns. Muddy vertical accretion deposits with ripples and convolutions cap each sequence.

RANGE OF SEDIMENTARY SEQUENCES

Channel Aggradation ⟷ Sand Flat Development



they deposit sets of planar crossbeds which would probably have paleocurrent directions at high angles to the trough crossbeds of the other channel deposits. The channel deposits contain intraclasts, ice-rafted cobbles, and organic debris which all accumulated as a scattered lag. The sediments of the channel aggradation sequence probably show only a very minor vertical grain size variation.

The sandy top of the channel aggradation sequence consists of small planar crossbeds and ripple cross-lamination which were formed by sand waves and ripples in minor channels (Chapters IV, V). These minor channels were topographically high in the system; as a result, sedimentation here did not differ much from sedimentation in other shallow areas, such as the margins of sand flats (Chapter VI).

It is impossible to estimate quantitatively how important this sequence would be in the deposits of this river. It is believed that channel aggradation sequences could be preserved in some cases. A sedimentary sequence consisting of trough crossbeds capped by floodplain deposits has been noted in a Devonian braided stream deposit (Cant and Walker, 1976).

The other end member sequence in Fig. 63 is the sand flat sequence. The lowermost unit in this sequence is inferred to consist of trough crossbeds deposited in a channel. The first stage in the formation of the sand flat itself involves the building of a high area on the top of a cross-channel bar. This acts as the nucleus of the sand flat. The location of the nucleus and its spatial relationships with other large geomorphic elements influences the morphology of the sand flat which forms. Small, newly-formed sand flats may be symmetric, asymmetric, or side flats. These morphologies are reflected in the paleocurrent patterns of the lower planar crossbed set in the sand flat deposit (Fig. 55).

The growth of a sand flat involves lateral and vertical bar accretion and linking by cross-channel bars (Chapter VI). The growth, therefore, deposits a variable number of planar crossbed sets above the initial one. The paleocurrent directions of these sets are highly variable, depending on the specific process which deposited them. Lateral bar accretion creates planar crossbed sets at very high angles to the river direction (Appendix 5). Vertical bar accretion may create sets which have highly variable directions (Appendix 5). Alternatively, sets may be formed which head downriver with low dispersion of directions because of very high flow sweeping directly over all obstacles. Only for side flats, where the bars all head inwards towards the bank is the pattern simple. In this case, all the planar sets have orientations at high angles to the river direction. Some vertical accretion parallel lamination may be intercalated within these planar crossbed sets.

On the margins and tops of high sand flats, the processes of shallow water sedimentation such as the migration of ripples and sand waves occurs. These processes cause the deposition of small planar crossbed sets and ripple cross-lamination, much the same as the sandy top of the channel aggradation sequence.

This sequence represents the full development of a sand flat or sand flat complex which may persist for years. The details of stratification are unpredictable, but the general pattern should be similar to the illustration (Fig. 63).

The middle sequence in Fig. 63 represents one intermediate case between the sand flat and channel aggradation sequences. In the area where this intermediate sequence was deposited, a cross-channel bar with a nucleus is visualized as forming, and some vertical and lateral accretion occurred. Several sets of planar cross-stratification were deposited by these processes. However, at some point, the development of the sand flat ceased and a shallow channel was re-established over the sand flat deposits. This channel was floored by small dunes which generated trough crossbeds. The channel then aggraded, much as any other shallow channel.

This intermediate sequence is only one of many which could possibly result. There is no life cycle of sand flats; rather they are subject to a series of possibly unrelated events which may affect them in different, essentially non-predictable ways. They may be converted into channels at any stage of their development. Therefore, the range of possible sedimentary sequences ranges from no sand flat development to complete development.

All three sections have been illustrated as being capped by fine-grained vertical accretion floodplain deposits. These deposits (Appendix 2) are composed of lenses and layers of sand which are commonly convoluted, in a bed of cohesive mud. It is believed that this capping of fine-grained deposits would comprise the top of the fluvial facies sequences. This deposit would be preservable in some cases, but this depends on factors such as the rate of subsidence of the area, and the pattern and rate of lateral migration of the river.

COMPARISON WITH OTHER FLUVIAL FACIES SEQUENCES

In Fig. 64(a), three facies sequences are illustrated which were inferred by Jackson (1976) to have been deposited by different parts of the meander bends in the Wabash River. In Fig. 64(b), two other facies sequences are presented. One is interpreted to represent braided river deposits in the Battery Point Formation (Cant and Walker, 1976), and the other to represent ancient meandering stream deposits (Allen, 1970). All of these should be compared with the facies sequences presented in Fig. 63.

FIG. 64(a). The three facies sequences deposited by the meandering Wabash River (after Jackson, 1976).

These different sequences are believed to be deposited by different parts of the meander bends. Note that little fining upward trend exists in the coarse members of the Transitional and Intermediate sequences. The paleocurrent directions do not deviate much from the downriver direction except for the planar crossbeds at the top of the coarse member of the Fully Developed sequences. This unit shows a very large deviation, in some cases over 90°.

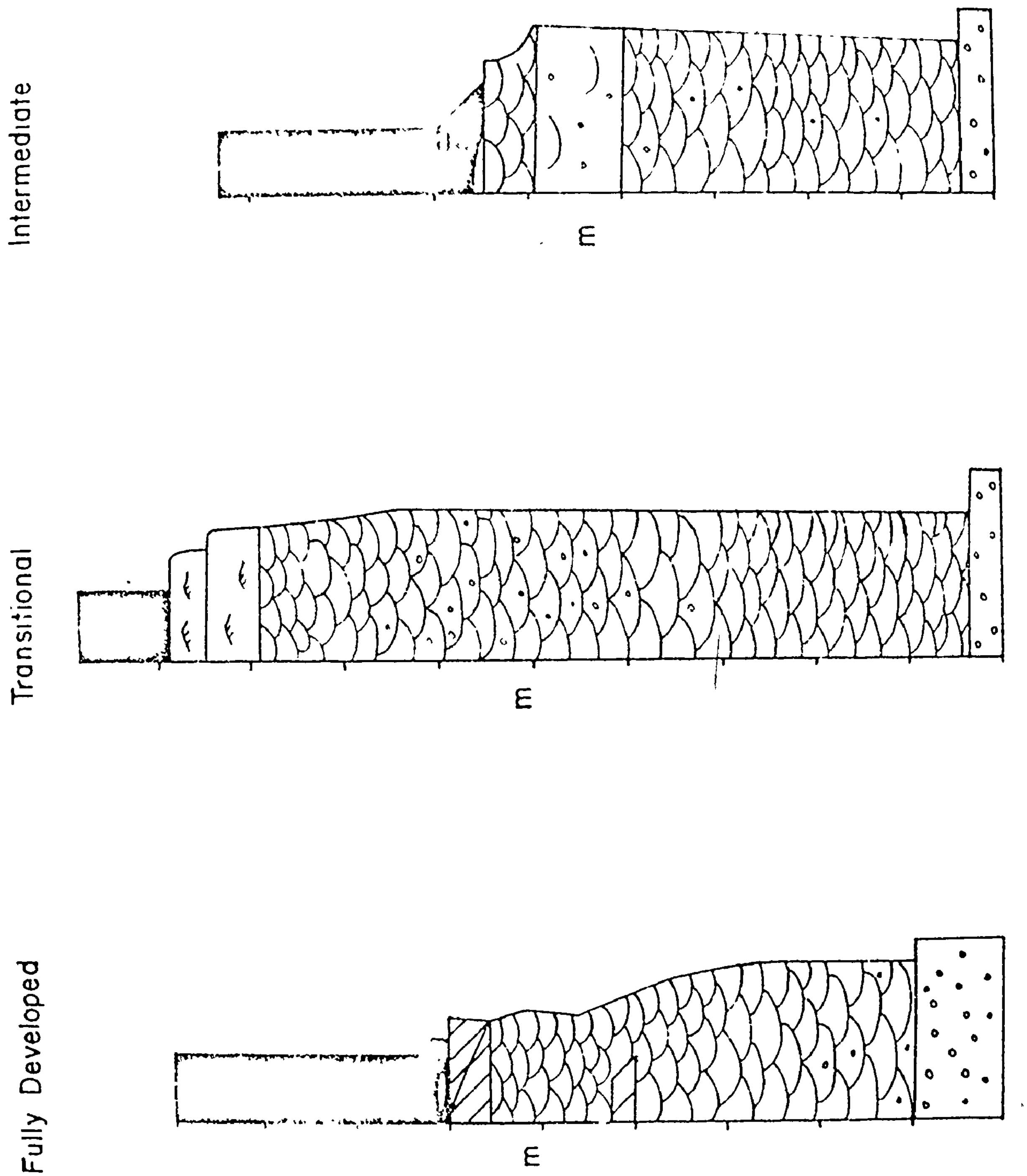
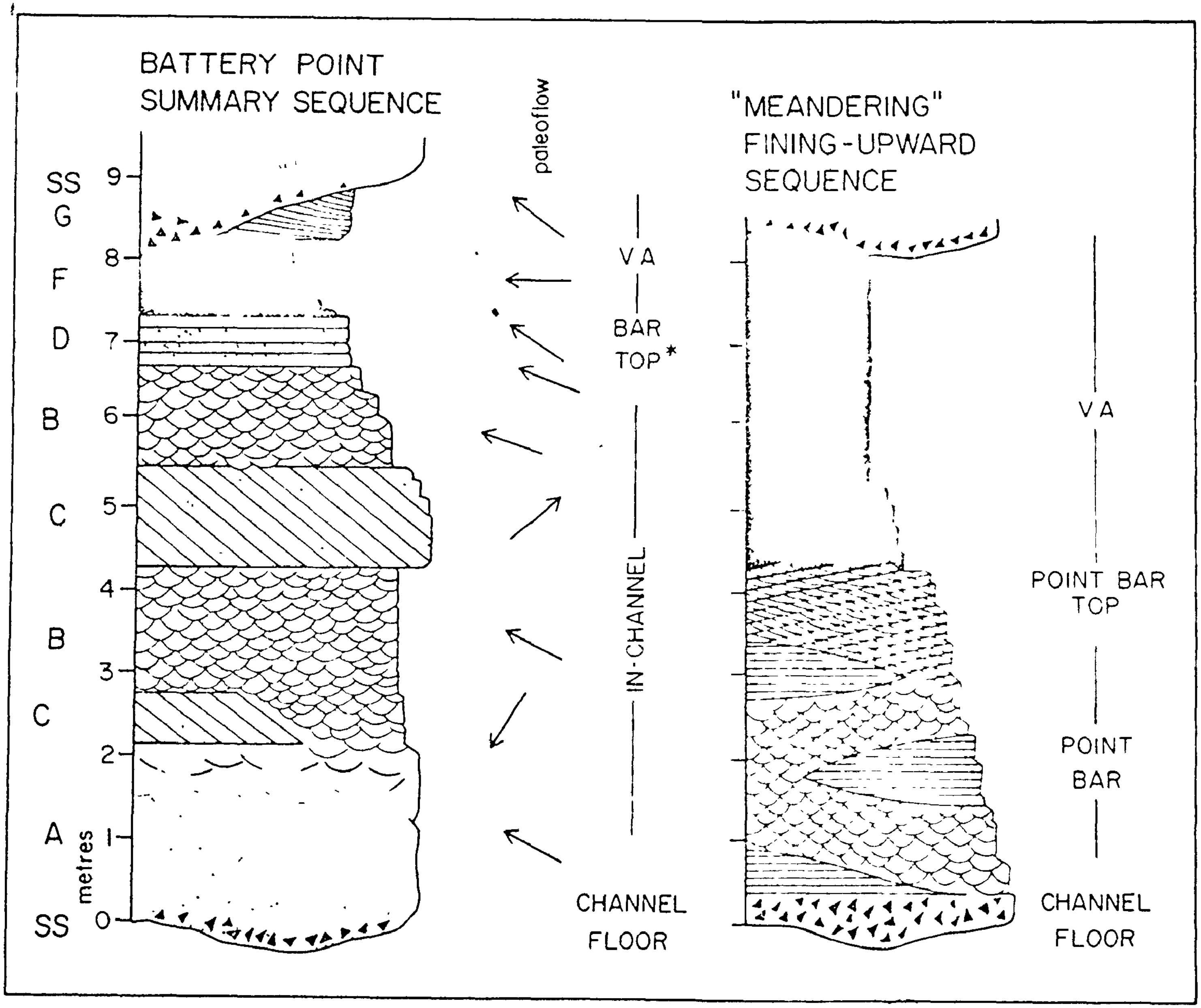

Intermediate
m
Transitional
m
Fully Developed
m

FIG. 64(b). The generalized facies sequence from the Battery Point Formation (Cant and Walker, 1976) and the facies sequence from many Devonian mandering stream deposits (after Allen, 1970).


BATTERY POINT
SUMMARY SEQUENCE
"MEANDERING"
FINING-UPWARD
SEQUENCE
paleoflow
SS
G
F
D
B
C
B
C
A
SS
metres
0
1
2
3
4
5
6
7
8
9
VA
BAR
TOP*
IN-CHANNEL
CHANNEL
FLOOR
VA
POINT BAR
TOP
POINT
BAR
CHANNEL
FLOOR

Inspection of all these sequences reveals that the facies sequences of the meandering Wabash and Allen's (1970) meandering stream sequence have the following noteworthy characteristics: 1) a relatively thick deposit of fine-grained muddy sediments at the top; 2) a lack of planar crossbed sets within the sand body. It should be noted that Jackson's facies sequences were compiled from a very limited number of trenches in four meander bends. Allen's data were compiled from many different areas of Devonian sediments, and therefore may include the deposits of several different types of rivers. The sand bodies in Jackson's sequences in some cases show no fining-upward tendency and have no parallel laminations. Although it is difficult to understand the reasons for these differences in the sequences, it may be that the Wabash River is more proximal and coarser-grained than most of the rivers which deposited the sequences reported by Allen.

The Battery Point sequence (Cant and Walker, 1976) and the South Saskatchewan sequences have the following similarities: 1) a thin or absent fine-grained muddy unit on top; 2) the presence of planar crossbed sets within the sand body (in some sequences); 3) little vertical trend in grain size in the sands. The Battery Point sequence is the result of a compilation of data from one fairly homogeneous rock section, and therefore may represent the deposits of a single type of river. Although the similarities mentioned above exist, nothing corresponding to Facies G of the Battery Point has been observed in the South Saskatchewan. It should be understood that sequences compiled from ancient sediments are not strictly the same as sequences which are envisioned to result from a modern environment. The two types have fundamentally different data bases. The preservation of deposits in the modern environment is not easily predicted. Longer-term processes are also difficult to understand. In spite of these reservations, and allowing for differences which may result from different tectonic settings, it is believed that the Battery Point sequence and the South Saskatchewan sequences are very comparable. This implies that the river system which deposited the Battery Point sediments was probably similar to the South Saskatchewan River.

Comparison between the meandering group and the braided group of sequences shows that trough crossbeds are common to all. This shows that sinuous-crested dunes are present in each type of river. The braided sequences have more planar crossbed sets, reflecting the presence of mid-channel braid bars, while the meandering sequences do not. The meandering stream sequences, in general, show more fine-grained muddy floodplain deposits. Both sequence types show sections which extend from channel bases to floodplains. However, the meandering sequences probably result from lateral channel migration (Allen, 1970), while the braided sequences probably result mostly from local vertical aggadation and diversion of flow elsewhere (Cant and Walker, 1976; Chien, 1961). The reasons for the different types of rivers are not clear, as was discussed in Chapter I.

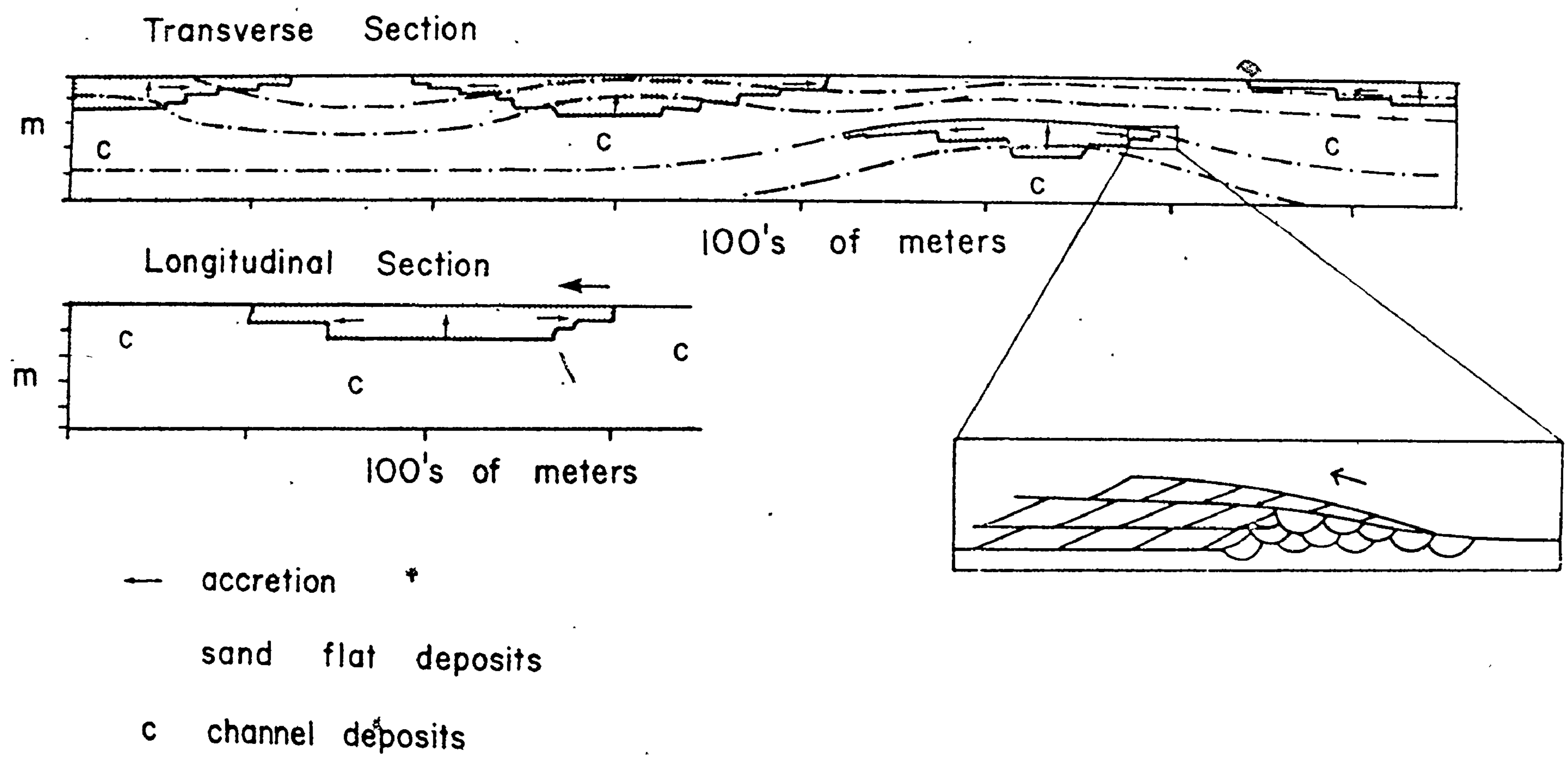
LATERAL RELATIONSHIPS

In Fig. 62, a few lateral relationships between sand flat and channel deposits were illustrated. Because a major sand flat or sand flat complex apparently forms from one or more small sand flats (Chapter VI), the sand flat deposits must gradually overstep the channel deposits, assuming a general aggradation of the bed locally. A sand flat accretes both laterally and vertically (Chapter VI), so the lateral transition from channel to sand flat deposits is inferred to occur farther towards the channel higher in the section. The sand flat deposits, therefore, should form a series of overstepping lenses of dominantly planar cross-stratification in an irregular body of dominantly trough cross-stratification. These relationships are illustrated in Fig. 65.

The angle of overstepping, however, will be very low. A sand flat which accretes laterally from 100 m to 400 m through a vertical thickness of 4 m will have an average angle of overstep of 1.5^{o}. The local value, however, may be much higher, particularly in the section parallel to flow. In these cases, trough crossbeds would pass in a short distance both laterally and vertically into planar crossbeds.

FIG. 65. Hypothetical lateral relationships between sand flats and channel deposits. The inset shows more detail of the overstepping planar crossbeds. The broken lines are time lines. The arrows in the sand flat deposits show directions of accretion of the sand flats.

LATERAL FACIES RELATIONS



LONG-TERM PROCESSES

Long-term processes such as net aggradation, river migration and stacking of fluvial facies sequences cannot be observed directly. However, these processes have important implications for the preservation of the river deposits, and will be discussed here briefly.

In the following sections, a net aggradation of the river is assumed in all cases. This, in turn, implies continued subsidence of the area, and an abundant supply of sand. These conditions have been met in many tectonic environments during the history of the earth, as proved by the large volumes of fluvial deposits in the ancient record. The South Saskatchewan River itself is not in a subsiding area, but has aggraded within the valley (Chapter II). It is, therefore, believed that this river provides a reasonably good analogy to rivers of this type in areas of large-scale subsidence.

(a) Channel Migration

The migration of major channels in the system will have a very great influence on the organization of the river deposits. In meandering streams, the directions of migration of individual channels in meander bends are relatively simple to predict, but in braided streams, no easily understood pattern of migration prevails. If channels aggrade without much lateral movement, the flow is progressively directed elsewhere. The resulting deposit will be composed of both channel and sand flat sediments. However, if major channels migrate laterally, they may remove most of the sand flat deposits, leaving only remnants of these, with mainly channel sediments being preserved.

It is likely that both of these processes occur. Their relative importance depends on the rate at which each operates. Rapid aggradation of a channel, in fact, may promote lateral migration of the flow over a sand flat because the channel becomes progressively shallower and less efficient as a conduit. This process would likely cause removal of the upper parts of the sand flat deposit. The sand flat and channel deposits would be intercalated with one another.

(b) River Migration

Because the river is flowing within a valley (Chapter II), it is prevented from migrating laterally. In situations where an aggrading braided river is not laterally confined, the entire river may switch its course. Coleman (1969) has documented the migration of the Brahmaputra River through several centuries. This migration is controlled, in part, by tectonic activity in the area. Campbell (1976) interpreted a Jurassic sheet sandstone up to 100 km wide (transverse to paleoflow) as being created by the lateral migration of a large sandy braided stream system. The sheet is composed of many large channels and channel systems. Sandy braided streams, therefore, may aggrade vertically and migrate laterally, thus leaving their deposits over a wide area.

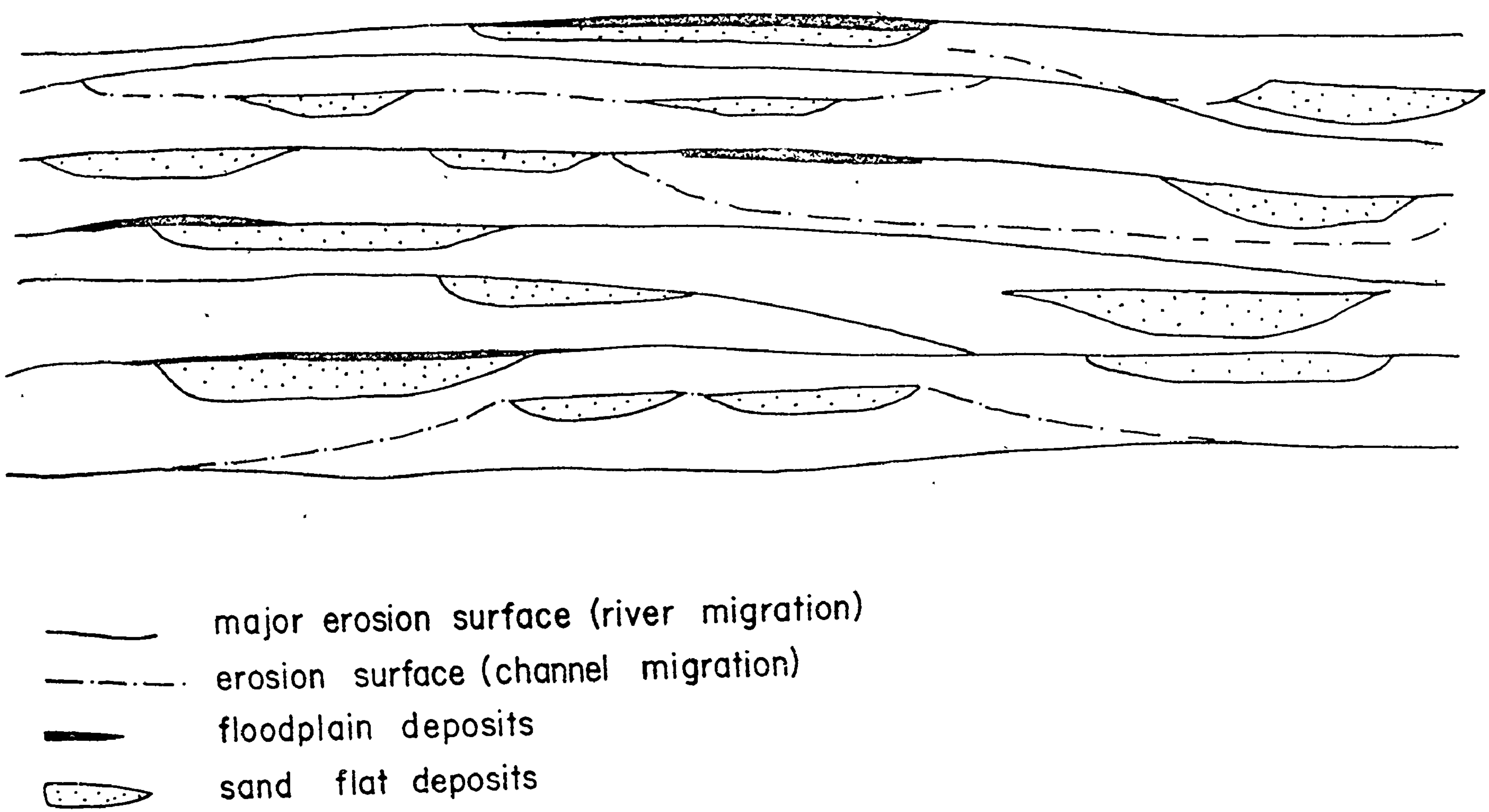
(c) Vertical Stacking of Facies Sequences

The lateral migration of a braided stream cannot continue indefinitely in one direction. The river then may migrate back over its own deposits, creating a new facies sequence on top of the old one. The depth to which the old sequence is eroded depends on a number of factors, such as the amount of subsidence of the area, the amount of cohesive sediment capping the older sequence, the erosive power of the stream, and the rate of aggradation of the active river. Most of these parameters are non-predictable because they are the result of long-term, slow processes. A great deal of variability of this depth may occur on a local scale, with major channels cutting deeply into older deposits in one place, but not in another. Because the fine-grained, cohesive floodplain sediments are thin (Appendix 2), they are relatively easily removed, thus further emphasizing the lack of fine sediment in braided river deposits.

It is believed that the stacking of vertical facies sequences by a river like the South Saskatchewan on an aggrading alluvial plain would generate a sand body which contained a few thin discontinuous mud beds. This sand body would contain laterally widespread erosion surfaces which represent the migration of the river back and forth, across the floodplain. These erosion surfaces act as the bounding surfaces for the facies sequences discussed earlier in this chapter (Fig. 66). Within the sequences, smaller erosion

FIG. 66. Hypothetical picture of the stacking of fluvial facies sequences. The figure represents a vertical thickness of 25 m and a width of about 800 m.

STACKING OF SEQUENCES



surfaces would be present, created by the lateral migration of channels within the system.

This scheme of organization of the deposits on this very large scale is a compilation based on this study, and studies of ancient braided stream deposits by McGowan and Groat (1971), Cant and Walker (1976) and Campbell (1976). The inherent variability of braided rivers makes any prediction of this type somewhat speculative; however, this large-scale model of sedimentation is consistent with the short-term processes and deposits observed in the South Saskatchewan River.

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APPENDIX 1

GRAIN SIZE DATA

Grain size data is presented in terms of phi units along the left side of the page. The cumulative decimal fraction of each sample is given in a column.

Sample locations -- on the map (p. 248).

1. Bed of minor channel near river bank
2. Lateral accretion bar
3. Protected area in lee of island
4. Drainage channel on sand flat
5. Bed of minor channel
6. Upstream end of mid-channel sand flat
7. 1/3 the way down
8. 2/3 the way down
9. Sand wave on margin
10. Channel lateral to sand flat
11. Downstream end
12. Protected area downstream
13. Lateral accretion bar

(6–13: Same sand flat)

14. Deep
15. Intermediate
16. Shallow

(14–16: Parts of a deep-shallow sequence in a major channel.)

phi	Sample 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
-2.00	.007	----	----	----	----	.008	----	.011	----	.002	----	----	----	----	----	----
-1.75	.022	.004	----	.003	.002	.020	.002	.025	----	.002	.005	----	.002	----	----	----
-1.50	.049	.016	.001	.003	.003	.030	.009	.036	----	.006	.012	----	.008	.054	----	.020
-1.25	.086	.046	.002	.006	.012	.039	.017	.049	----	.017	.029	----	.023	.065	----	.034
-1.00	.125	.083	.004	.008	.025	.054	.031	.066	.002	.032	.060	.002	.047	.084	----	.058
- .75	.147	.094	.004	.008	.030	.060	.037	.071	.002	.038	.067	.003	.055	.112	.016	.076
- .50	.179	.123	.005	.010	.041	.070	.053	.082	.003	.051	.082	.006	.066	.139	.018	.101
- .25	.215	.156	.006	.013	.054	.081	.074	.094	.004	.066	.101	.009	.083	.168	.022	.123
00	.257	.190	.007	.018	.071	.097	.104	.112	.006	.091	.130	.016	.104	.203	.027	.146
.25	.306	.229	.008	.026	.094	.116	.140	.137	.010	.125	.169	.024	.132	.248	.033	.171
.50	.361	.266	.010	.037	.121	.139	.182	.170	.017	.169	.216	.038	.168	.302	.049	.198
.75	.428	.313	.012	.058	.160	.169	.227	.215	.028	.231	.276	.062	.210	.385	.070	.232
1.00	.527	.388	.017	.110	.225	.226	.287	.295	.052	.338	.377	.116	.281	.531	.116	.281
1.25	.620	.460	.023	.174	.292	.291	.339	.388	.072	.445	.478	.182	.347	.654	.175	.331
1.50	.738	.565	.037	.311	.409	.412	.419	.540	.122	.606	.622	.295	.445	.825	.325	.405
1.75	.839	.670	.060	.524	.544	.551	.517	.703	.194	.756	.757	.420	.551	.933	.546	.473
2.00	.921	.786	.109	.792	.690	.760	.653	.872	.320	.882	.875	.463	.684	.985	.810	.652
2.25	.952	.854	.154	.904	.766	.778	.735	.937	.444	.936	.927	.650	.792	.994	.913	.779
2.50	.975	.915	.245	.966	.852	.860	.817	.975	.635	.974	.969	.768	.900	.999	.970	.894
2.75	.990	.957	.420	.991	.930	.920	.878	.989	.822	.992	.937	.851	.955	1.00	.988	.957
3.00	.997	.979	.555	1.00	.968	.953	.913	.994	.908	.997	.993	.910	.981	----	.996	.985
3.25	1.000	.993	.699	1.01	.989	.979	.948	.998	.964	.999	.997	.957	.993	----	1.00	.995
3.50	1.00	.997	.787	----	.995	.991	.973	.999	.985	.999	.998	.978	.997	----	----	1.00
3.75	1.00	.998	.878	----	.998	.996	.988	.999	.994	1.00	.999	.988	.998	----	----	----
4.00	1.00	.999	.907	----	.998	.997	.992	1.00	.995	----	.999	.990	.999	----	----	----
4.00	----	1.00	1.00	----	1.00	.999	1.00	----	1.00	----	1.00	1.00	1.00	----	----	----

APPENDIX 2

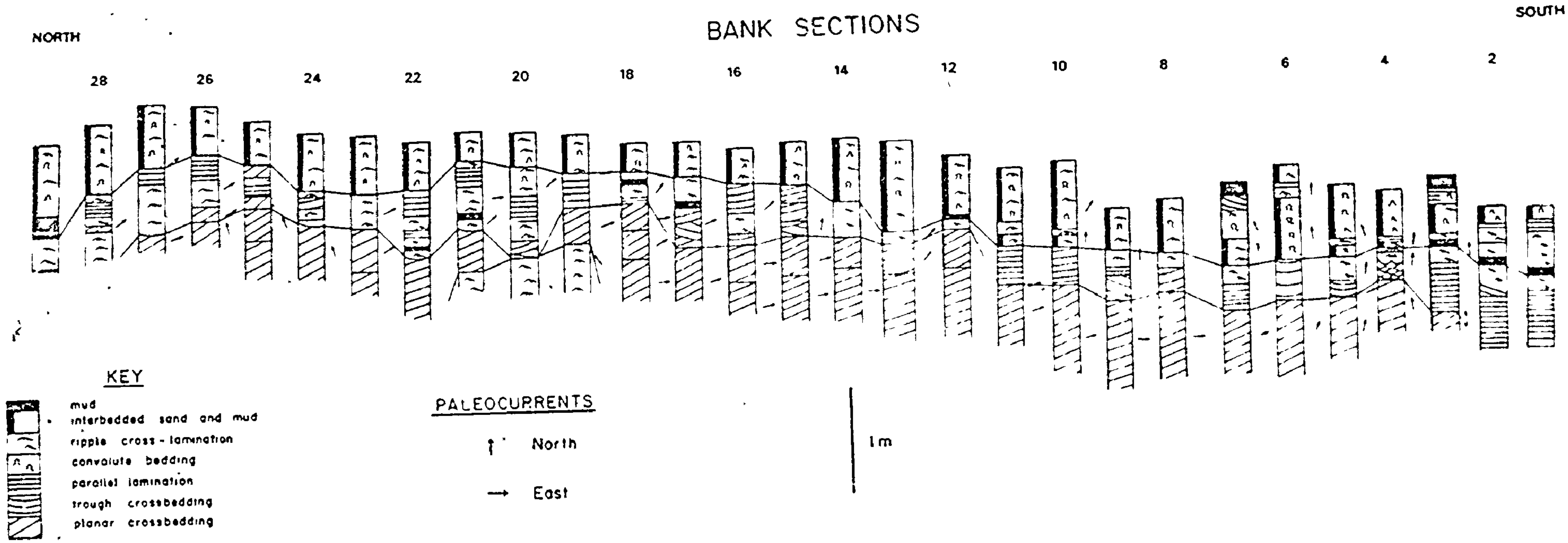
RIVER BANK SECTIONS

These sections were measured on the east bank of the river 600 m upstream from the road bridge at Outlook. They are separated laterally by 5 to 9 m in each case, and represent a total length of approximately 240 m. They are presented from right to left just as they were seen on the river bank, proceeding downstream from 1 to 29.

The sections have been divided in most cases into three units. The bottom two are sand, and are believed to be a sand flat deposit (see Chapter VI). The paleocurrent directions in these units are mainly eastward, heading in towards the bank. These units are believed to represent a side flat for this reason (Chapter VI).

The upper unit is a vertical accretion floodplain deposit composed of cohesive sandy mud. Many irregular lenses and layers of rippled sand exist in this, most of which exhibit convolutions. In a few of the layers, the sand is composed of low angle or horizontal laminations. Many roots bind this upper unit together. This description could be applied to all the muddy floodplain deposits in the river valley.

Other bank sections in the river were very similar to this one. No other bank was found which was exposed so well as this one. Most of the banks in the river were damaged by the floods of 1974 and 1975, with the result that they could not be excavated because of the roots and fallen floodplain material.


BANK SECTIONS
NORTH
SOUTH
28
26
24
22
20
18
16
14
12
10
8
6
4
2
KEY
mud
interbedded sand and mud
ripple cross-lamination
convolute bedding
parallel lamination
trough crossbedding
planar crossbedding
PALEOCURRENTS
North
East
1m

APPENDIX 3

HYDRAULIC DATA

The hydraulic data in this appendix consists of velocity profiles measured over active bedforms. The velocity measurements were made with a Price-type current meter held in the flow on a rod. Each velocity measurement is the result of a one-minute reading, so is an average velocity.

The data is presented in the following format:

	Location Code Bedform type		
	3	20	
	6	25	
	9	30	
Depths in cm	12	35	Corresponding velocities in cm/sec
	15	40	
	18	45	
	21	48	
Total depth	23		

For the key to the location code, see the location map (p. 248).

A Dunes

6	48
9	50
12	55
15	58
18	51
26	

A Dunes

6	39
9	47
12	48
15	59
18	53
21	50
24	48
31	

B Sand Waves

6	28
12	40
18	46
24	55
31	54
37	52
43	54
49	50
55	

B Sand Waves

6	44
12	48
15	49
18	52
24	55
31	54
37	57
43	58
49	55
57	

A Dunes

6	32
12	49
15	49
18	52
24	55
31	55
37	56
43	63
49	58
52	57
58	

A Dunes

6	38
12	47
15	50
18	52
24	55
31	57
37	60
43	52
49	

A Dunes

6	45
12	52
15	55
18	58
24	60
31	62
37	66
43	59
50	

B Sand Waves

6	38
12	45
18	46
24	47
31	50
37	43
40	

C Sand Waves

6	44
15	44
24	55
34	55
46	65
58	63
73	62
86	68
104	69
119	65
134	68
149	
155	

C Sand Waves

9	39
21	56
31	52
46	58
60	67
76	65
91	66
107	76
122	73
137	74
140	64
143	

C Sand Waves

9	30
21	50
31	55
43	56
60	67
76	67
91	65
107	73
122	66
128	56
131	

C Sand Waves

9	36
21	44
31	51
46	63
60	59
76	64
91	65
107	67
116	57
122	

D Dunes

23	77
90	83
113	

E Dunes

16	50
66	71
82	

F Ripples

16	36
63	55
79	

F Dunes

15	57
59	72
73	

G Sand Waves

6	35
12	40
18	44
24	49
31	50
37	54
43	45
46	

G
Sand Waves

6	38
12	45
18	47
24	50
31	54
37	43
39	

G
Sand Waves

6	34
12	41
18	44
24	47
31	47
37	46
41	

G
Dunes

6	58
12	67
18	69
24	72
31	68
37	72
43	62
46	

E
Dunes

9	86
15	90
21	85
27	87
31	78
34	

E
Dunes

9	73
15	73
21	76
27	75
31	75
35	

E
Dunes

6	71
12	75
18	62
24	

E
Dunes

6	46
12	56
18	65
24	68
31	69
37	70
43	63
49	

H
Sand Waves

9	37
21	48
34	49
46	52
58	48
70	60
82	64
95	62
107	54
118	55
125	

I
Ripples

9	22
21	31
34	31
46	38
60	43
76	47
91	52
107	54
122	55
137	54
146	

J
Dunes

9	34
18	48
27	55
37	59
46	62
55	62
64	60
73	65
79	57
82	

J
Sand Waves

9	37
18	45
31	50
43	50
55	56
67	55
79	55
91	55
104	52
107	

K
Ripples

9	27
27	36
46	48
60	52
76	52
91	59
107	59
122	64
137	62
152	59
162	48
165	

L
Dunes

9	50
18	56
27	62
37	64
46	66
55	66
64	74
73	72
79	67
82	

L
Dunes

15	67
31	71
46	75
60	81
76	83
91	87
107	85
122	87
137	81
143	

M
Dunes

15	68
31	71
46	77
60	84
76	83
91	86
107	84
116	59
119	

M
Ripples

7	31
29	45
37	

N
Ripples

15	40
60	57
76	

N
Ripples

9	37
37	47
46	

J
Dunes

31	64
46	71
60	77
76	84
91	85
107	87
122	87
137	86
152	84
162	

M
Dunes

15	59
31	69
46	76
60	75
76	81
91	81
107	78
119	

M
Dunes

12	49
24	56
37	66
49	68
60	69
70	

A
Sand Waves

6	27
24	45
31	

O
Ripples

15	51
31	64
46	67
60	72
76	72
85	68
91	

O
Ripples

15	36
31	40
46	41
60	45
76	47
91	47
107	49
122	

G
Ripples

7	35
27	48
34	

G
Ripples

15	29
60	39
76	

N
Ripples

10	36
39	50
49	

N
Ripples

6	29
24	38
31	

N
Dunes

10	47
41	61
52	

B
Sand Waves

7	31
29	53
37	

B
Sand Waves

8	26
32	48
40	

P
Sand Waves

9	27
34	45
43	

P
Sand Waves

6	22
24	36
31	

P
Sand Waves

8	27
32	38
40	

P
Sand Waves

7	28
29	44
37	

C
Sand Waves

6	33
24	43
31	

Q
Ripples

7	38
27	47
34	

Q
Ripples

7	33
27	48
34	

Q
Ripples

7	27
27	37
34	

G
Sand Waves

15	35
31	41
46	45
60	46
70	

G

Sand	Waves
15	47
31	49
46	53
60	57
76	57
91	62
107	46
110	

R

Sand	Waves
12	35
24	39
37	43
49	44
60	46
76	41
79	

R

Sand	Waves
12	34
24	40
37	41
49	45
58	43
64	

R

Sand	Waves
9	31
18	36
27	39
37	43
46	37
49	

R

Sand	Waves
9	29
18	36
27	40
37	38
40	

R

Sand	Waves
9	28
18	39
27	38
37	39
43	

R

Sand	Waves
9	16
18	28
27	34
37	36
46	37
52	

R

Sand	Waves
12	34
24	41
37	47
49	50
60	56
73	56
76	47
82	

R

Sand	Waves
12	38
24	45
37	47
49	50
60	52
70	47
73	

S

Sand	Waves
15	36
30	43
46	43
60	46
76	52
91	53
107	53
122	

S

Sand	Waves
12	36
24	43
37	46
49	49
60	52
73	54
85	56
95	49
98	

S

Sand	Waves
12	39
24	50
37	55
49	55
60	56
70	49
76	

P

Sand	Waves
9	40
18	50
27	56
37	57
46	59
55	63
64	59
73	

P

Sand	Waves
12	44
24	48
37	52
49	53
60	55
73	57
79	47
85	

P

Sand	Waves
15	46
30	52
46	49
60	57
76	59
91	59
107	62
119	50
122	

P

Sand	Waves
15	44
31	50
46	52
60	58
76	59
91	59
107	61
122	

P

Sand	Waves
15	45
31	48
46	53
60	57
76	61
91	62
107	64
122	59
128	

P

Sand	Waves
12	52
24	48
37	55
49	53
60	55
73	57
79	44
82	

P

Sand Waves

12	43
24	53
37	57
49	58
60	58
73	59
79	52
85	

P

Sand Waves

15	41
31	49
46	54
60	56
76	56
91	53
98	

R

Dunes

15	67
31	71
46	75
60	77
76	85
85	

R

Sand Waves

12	34
24	37
37	47
49	48
55	40
58	

R

Sand Waves

15	47
31	54
46	57
60	61
76	61
85	48
89	

R

Sand Waves

15	50
31	56
46	63
60	64
76	55
82	

R

Dunes

12	58
24	63
37	67
49	69
60	74
67	56
70	

R

Dunes

9	63
15	66
21	57
26	

R

Dunes

15	47
31	62
46	65
60	75
76	81
91	81
107	90
122	87
137	92
146	

R

Dunes

9	57
18	70
27	72
37	71
46	73
60	77
73	73
82	

R

Dunes

12	59
24	72
37	75
49	78
60	63
67	

P

Sand Waves

15	46
31	53
46	52
60	58
76	62
91	63
107	64
116	54
122	

P

Sand Waves

15	43
31	47
46	51
60	52
76	56
91	57
107	61
122	58
137	59
143	

P

Sand Waves

15	38
31	43
46	48
60	54
76	55
91	56
107	57
122	61
137	

N

Dunes

15	61
31	74
46	76
60	84
76	80
89	73
95	

N

Dunes

15	59
31	66
46	74
60	73
76	80
91	76
101	

L

Dunes

9	53
18	63
27	70
37	68
43	56
46	

M

Ripples

15	37
31	44
46	47
60	52
76	52
91	55
107	50
113	

M
Ripples

12	27
24	36
37	41
49	40
60	43
67	40
70	

M
Ripples

12	41
24	50
37	54
49	57
60	61
70	57
79	

M
Ripples

15	50
31	62
46	64
60	72
76	68
82	68
89	

S
Ripples

15	40
31	44
46	53
60	50
76	54
89	46
91	

P
Dunes

15	46
31	54
46	59
60	62
73	49
79	

P
Dunes

15	47
31	56
46	62
60	61
76	55
82	

P
Dunes

12	45
24	55
37	64
49	59
60	67
67	62
76	

P
Dunes

12	48
24	57
37	58
49	65
60	66
70	56
73	

P
Ripples

9	43
18	50
27	57
37	58
43	48
46	

P
Ripples

15	49
31	50
46	59
60	65
76	64
91	66
101	57
107	

M
Ripples

15	36
31	43
46	46
60	50
76	50
91	56
107	59
119	42
122	

M
Ripples

15	53
31	62
46	64
60	66
76	74
91	71
107	64
119	66
128	

I
Dunes

15	44
31	62
46	71
60	66
76	78
91	81
107	81
122	84
137	86
152	86
168	83
177	

J
Ripples

12	34
24	38
37	43
43	38
49	

R
Dunes

12	48
24	54
37	61
49	63
60	68
70	63
73	

R
Dunes

15	46
31	61
46	65
60	67
70	56
76	

R
Dunes

12	62
24	69
37	75
49	75
58	59
60	

R
Dunes

12	50
24	59
37	65
49	67
60	63
64	

R
Dunes

12	56
24	65
37	63
49	65
55	53
58	

R

Dunes

12	57
24	62
37	64
49	68
55	49
59	

R

Ripples

12	40
24	54
37	58
49	62
58	

R

Ripples

12	53
24	61
37	66
46	53
52	

T

Ripples

12	34
24	40
37	45
49	48
60	49
70	44
73	

T

Ripples

6	20
12	35
18	40
24	38
29	

APPENDIX 4

ECHO SOUNDER RECORDS

In this Appendix, typical echo sounder records are presented. The location of each profile is marked on the map (p. 248).

Top Profile

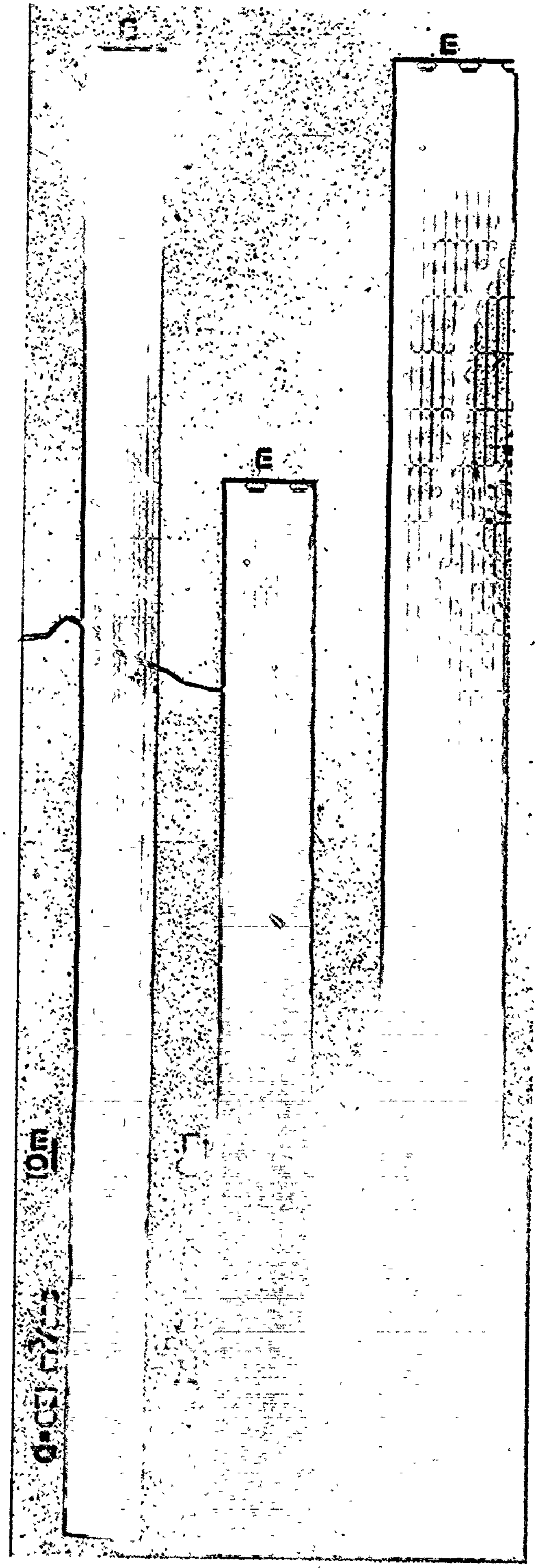
One deep to shallow channel sequence is shown with the variation in bedforms along it. In the deeper water, moderate-sized dunes are present, but these diminish in amplitude up to the crest of the shallow area. Beyond this, a few bar fronts occur on the down-slope.

Middle Profile

This profile shows the typical assemblage of dunes which occur on the channel beds at moderate stages.

Bottom Profile

This profile was made down a fast-flowing channel with fairly large dunes with deep scour troughs on its bed. The dunes range from triangular forms to irregular flat-topped forms. The deeper water on the right occurs where two channels converge against a stable bank. Only very low amplitude bed-forms are present in this unusual area.


E
E

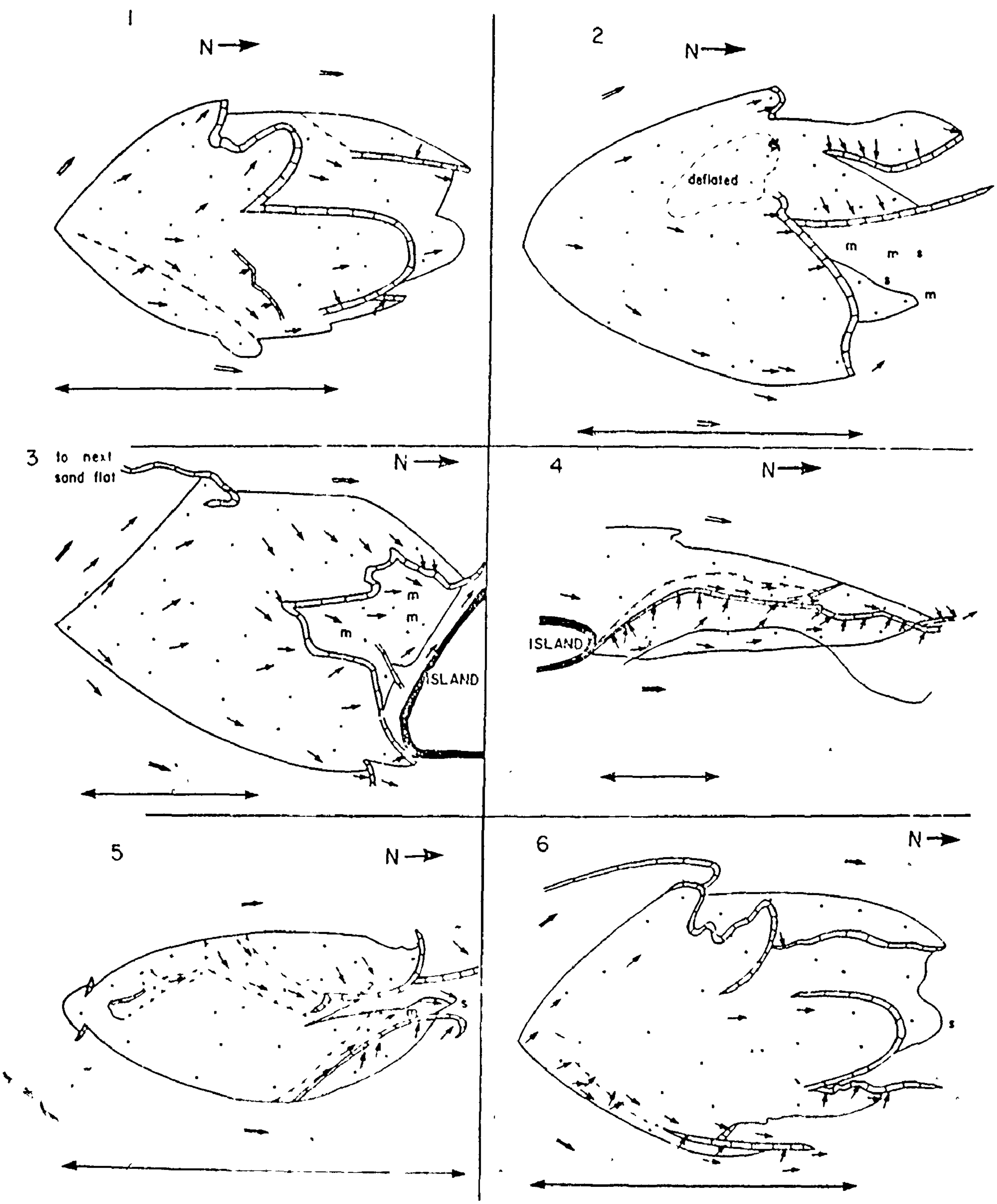
APPENDIX 5

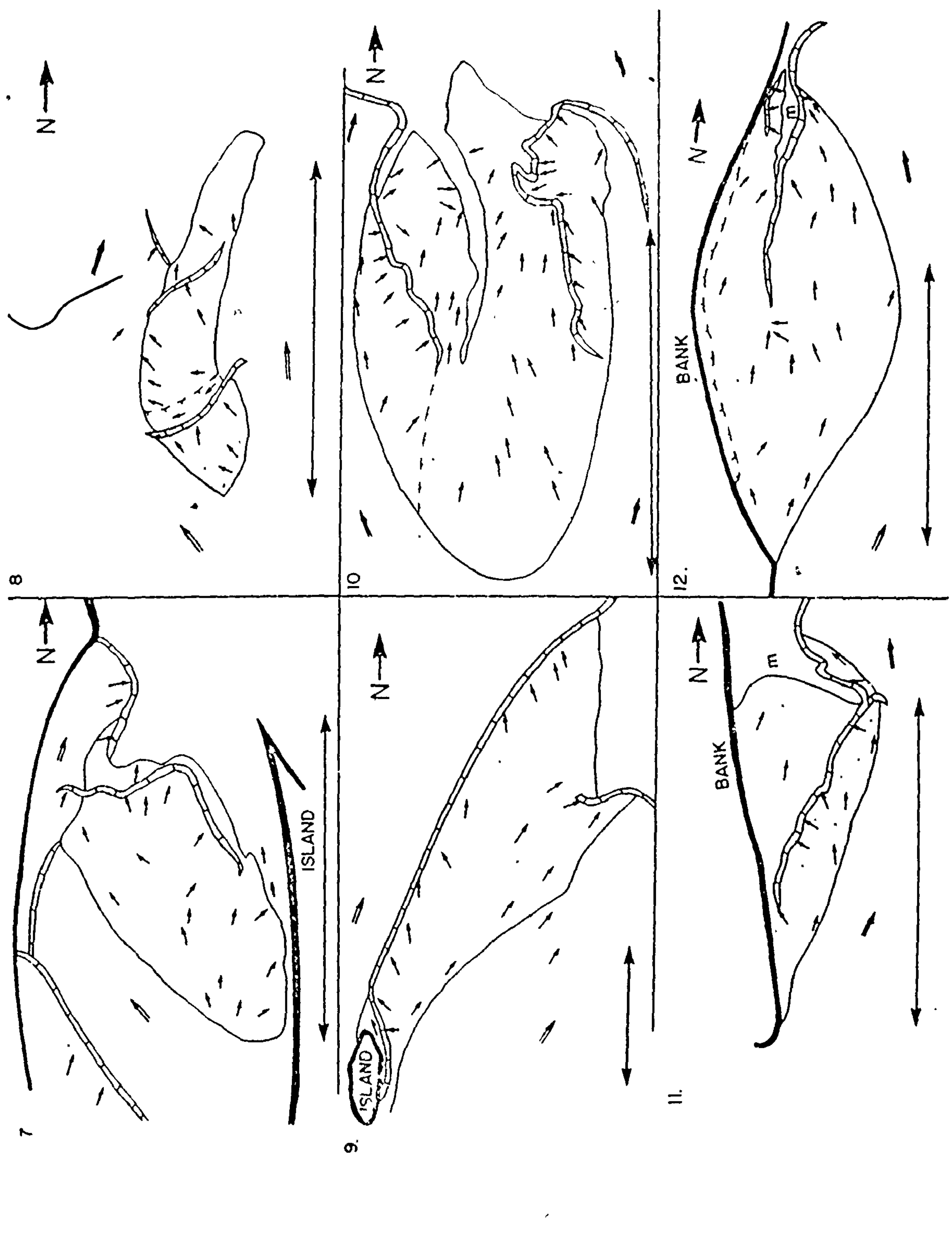
MAPS OF SAND FLATS

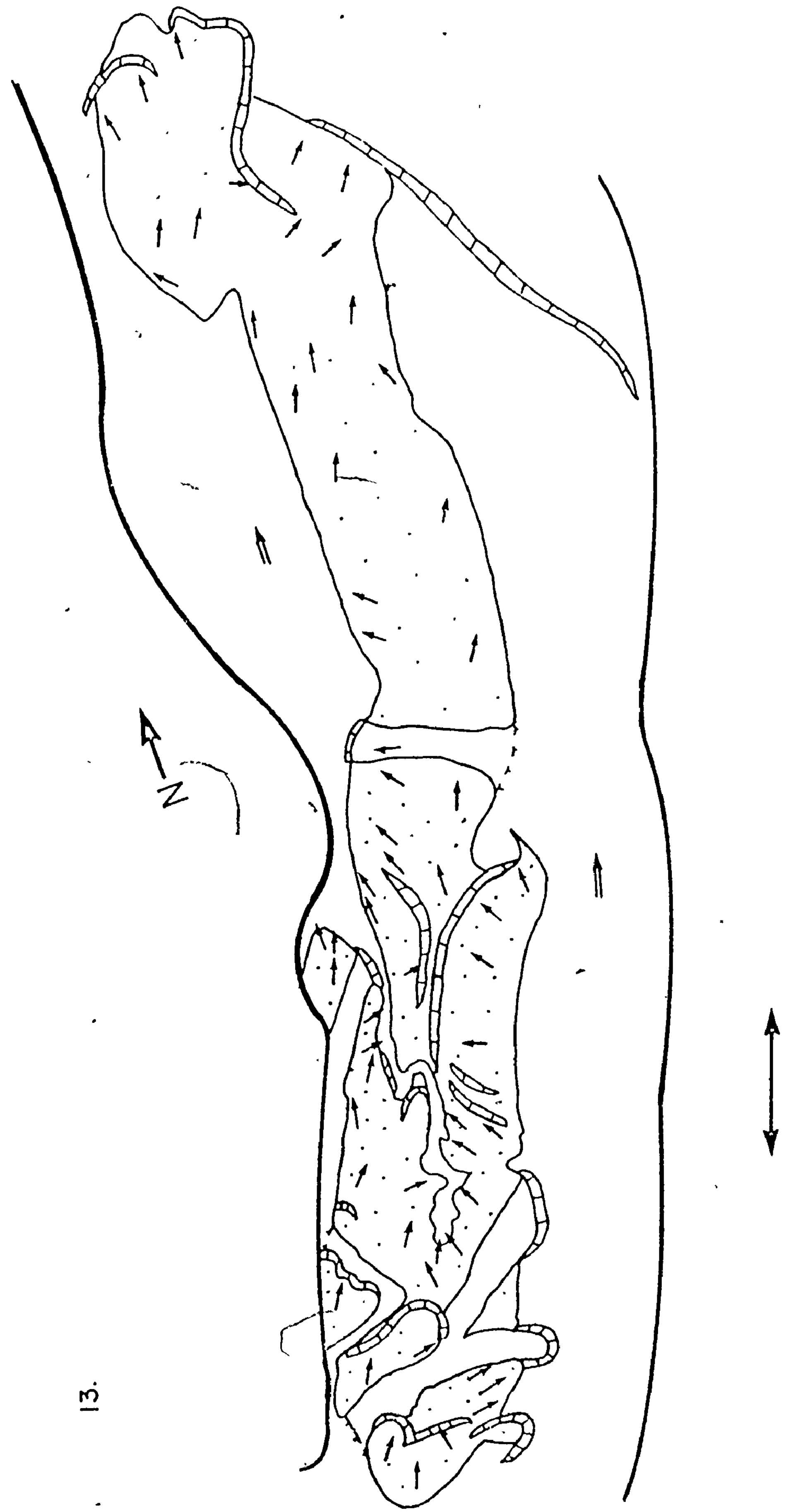
In this Appendix, 13 maps of sand flats are presented. These maps are the result of pace and compass mapping of major features and bedforms on selected sand flats, mostly in 1974. The maps are mostly correct, but certain dimensions are estimated.

The bar scale pointed on both ends below each map represents 100 m. The maps are highly variable in scale. The symbols used are the same as those in maps throughout the text, with the exception of a double arrow indicating current flow, and a single arrow indicating the direction of bedform advance.

The location of each sand flat is shown on the map (p. 248).


1
N
2
N
deflated
m
m
s
s
m
3
to next sand flat
N
m
m
m
ISLAND
4
N
ISLAND
5
N
s
m
6
N
s


7
8
9
10
11
12
N
ISLAND
ISLAND
BANK
BANK
m
m



13.

THE LARGE SCALE MAP

The map at the back of the thesis shows the entire length of the river which was considered in this study. The map is a compilation from air photos by the method discussed in Chapter III. The air photos are numbers 30 - 168 of set YC-2014, obtained from the Saskatchewan Department of Natural Resources. These are the air photos referred to by number in captions to figures throughout the thesis. The numbers of some photos are shown on the east bank of the river. The locations of Government survey reaches discussed in Chapter II are shown on the west bank, i.e., R21. All the major elements of sufficient size are illustrated on this map. The locations of the stage recorder and the bridge near Outlook are also shown.

Data Location Map

The locations of the data presented in Appendices 1, 3, 4, and 5 are shown on this map of the intensive study reach near Outlook (note Railway Bridge). Figures 2, 13, 16, and 38 are also of this stretch of river.

Sediment Samples -- The locations of the samples of Appendix 1 are given as follows: 1, 2, ..., 16.

Hydraulic Data -- The capital letter which is the location code of each profile in Appendix 3 is marked on the map as A, B, ..., T.

Echo Sounder Records -- The tracks of the echo soundings are indicated as dotted lines with small letters a, b, c, and d beside them.

a -- The approximate paths of the 4 profiles in fig. 25 (p. 90).

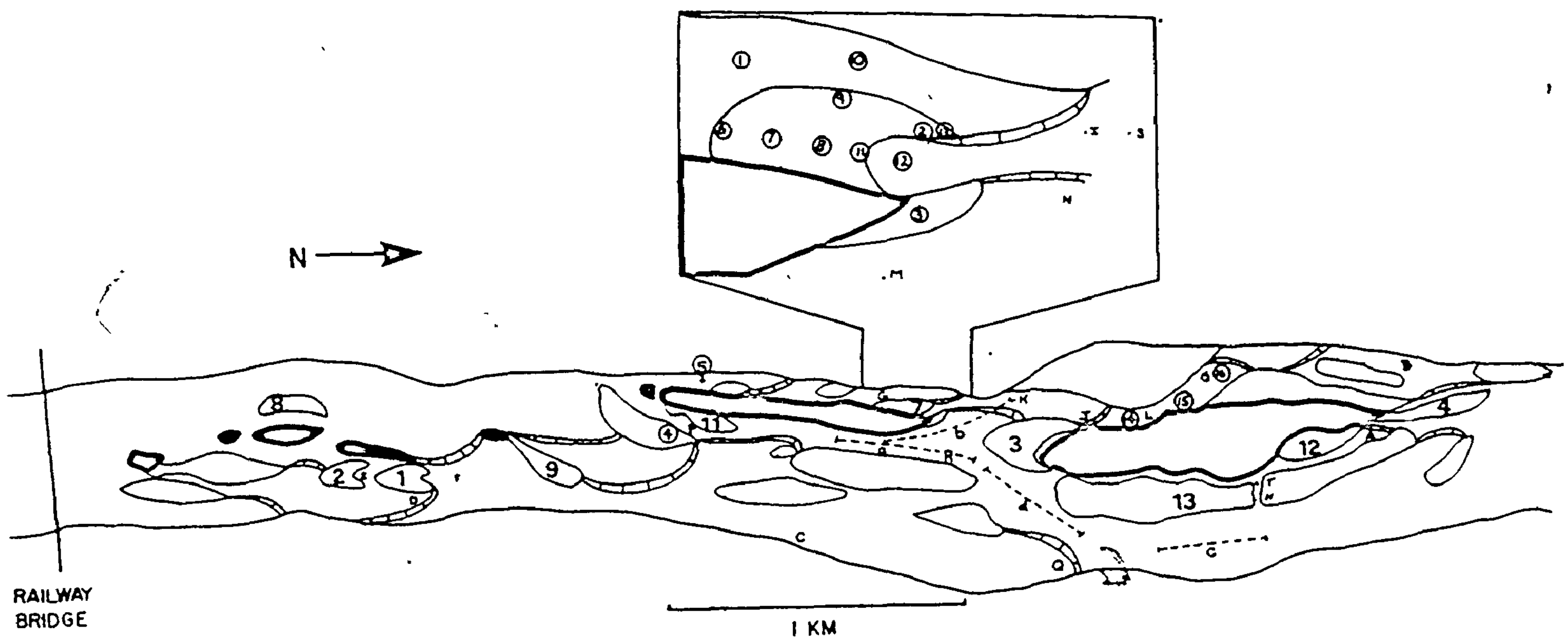
b -- The path of the upper profile in Appendix 4.

c -- The path of the middle profile in Appendix 4.

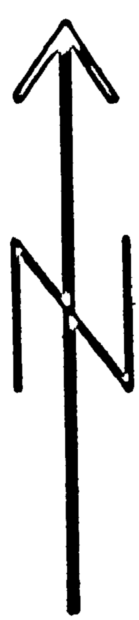
d -- The path of the lower profile in Appendix 4.

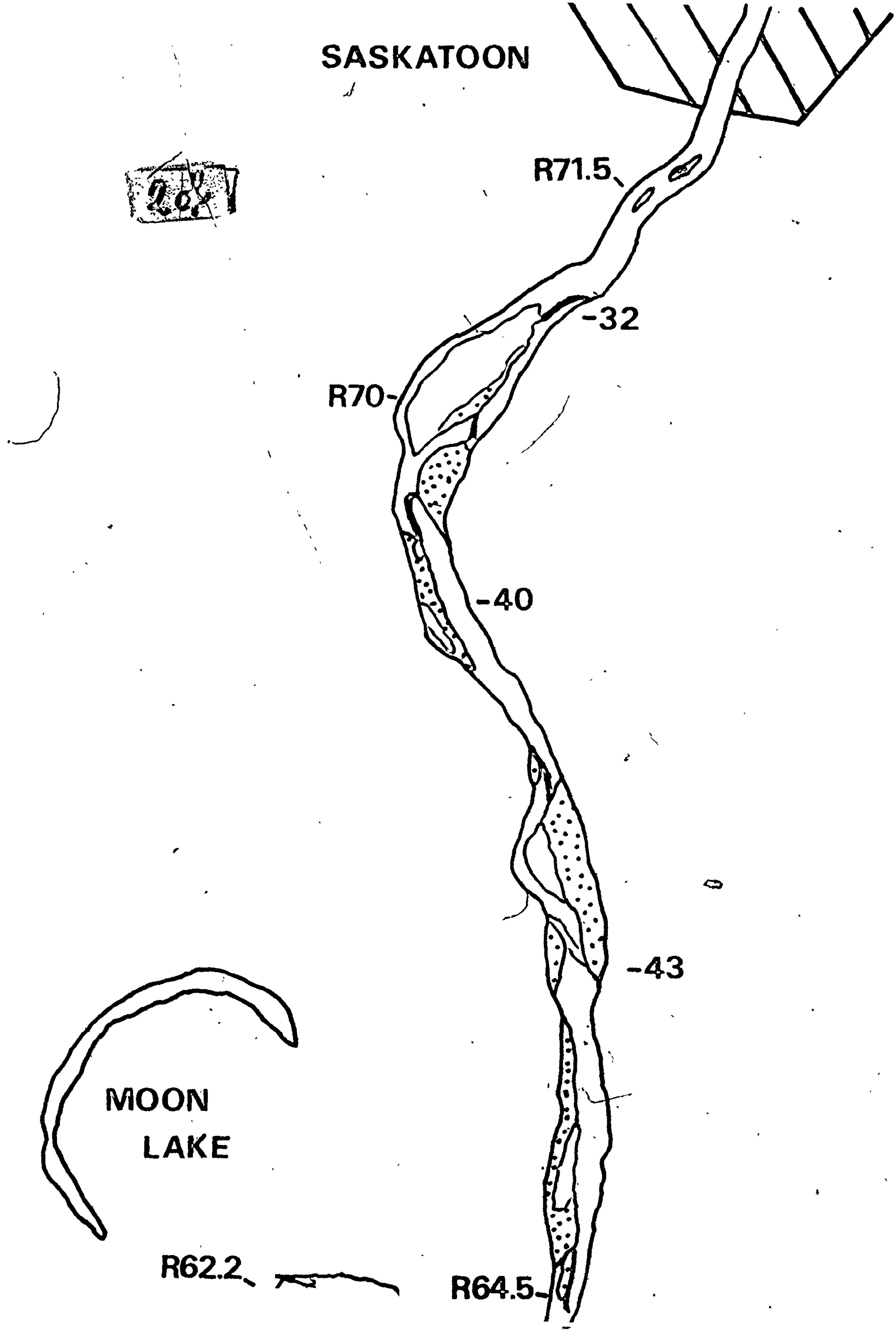
Maps of Sand Flats -- The locations of the sketch maps in Appendix 5 are shown by large numbers 1 to 13 except for 5, 6, and 10. These sand flats occur in approximately the same positions as sand Flats 11, 1, and 2 respectively. Sand Flats 5, 6, and 10 were changed or completely obliterated before the location map was prepared.

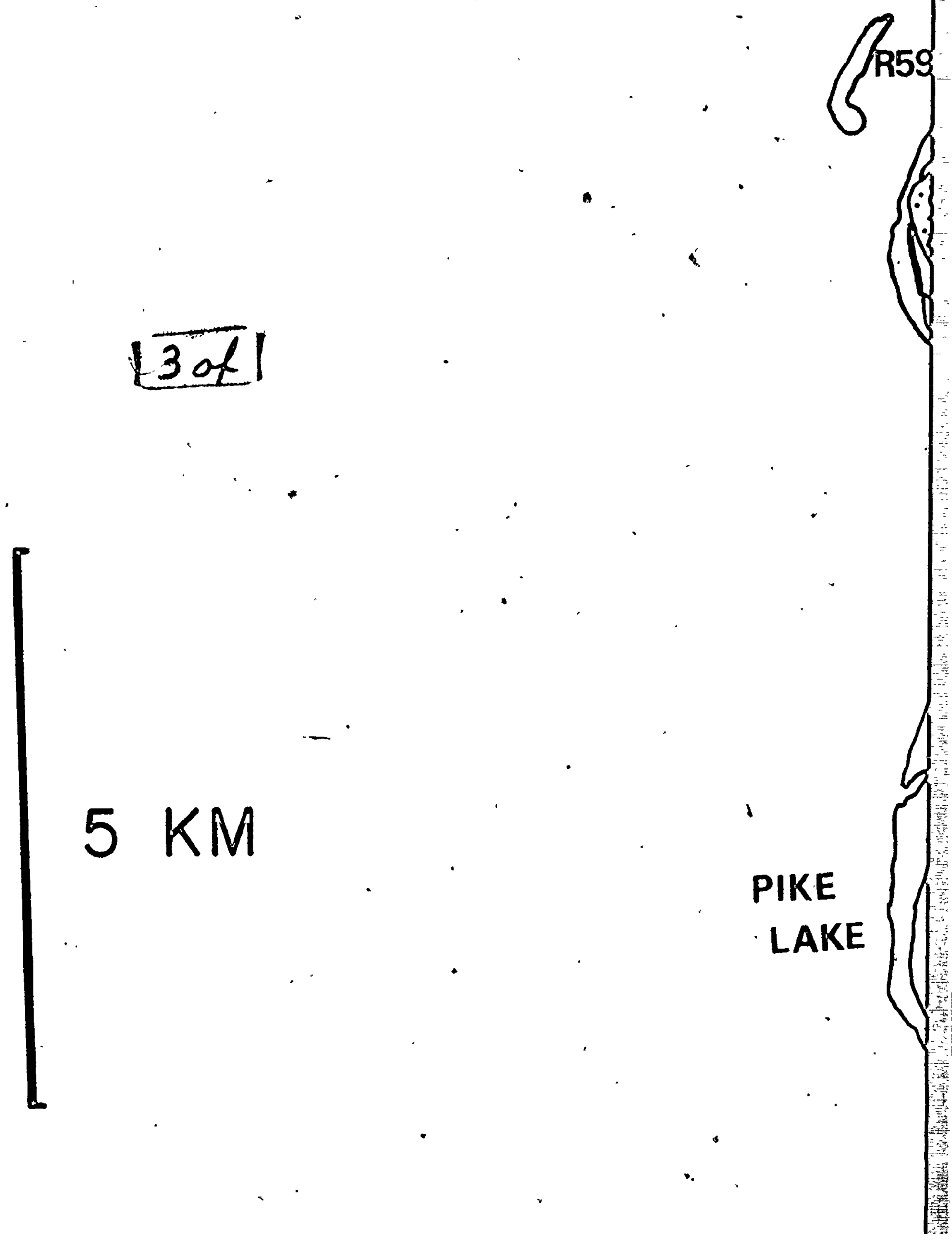
DATA LOCATION MAP

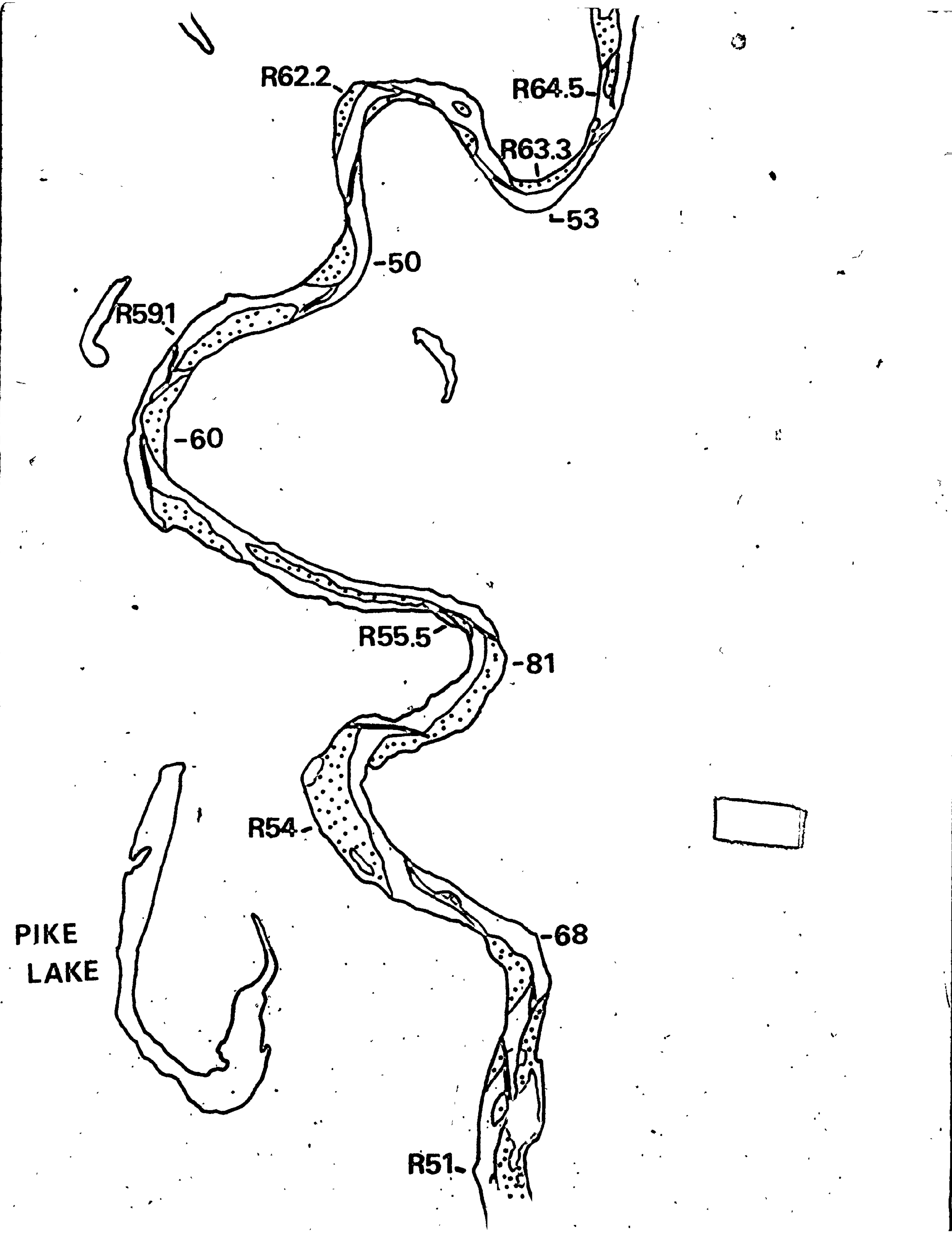


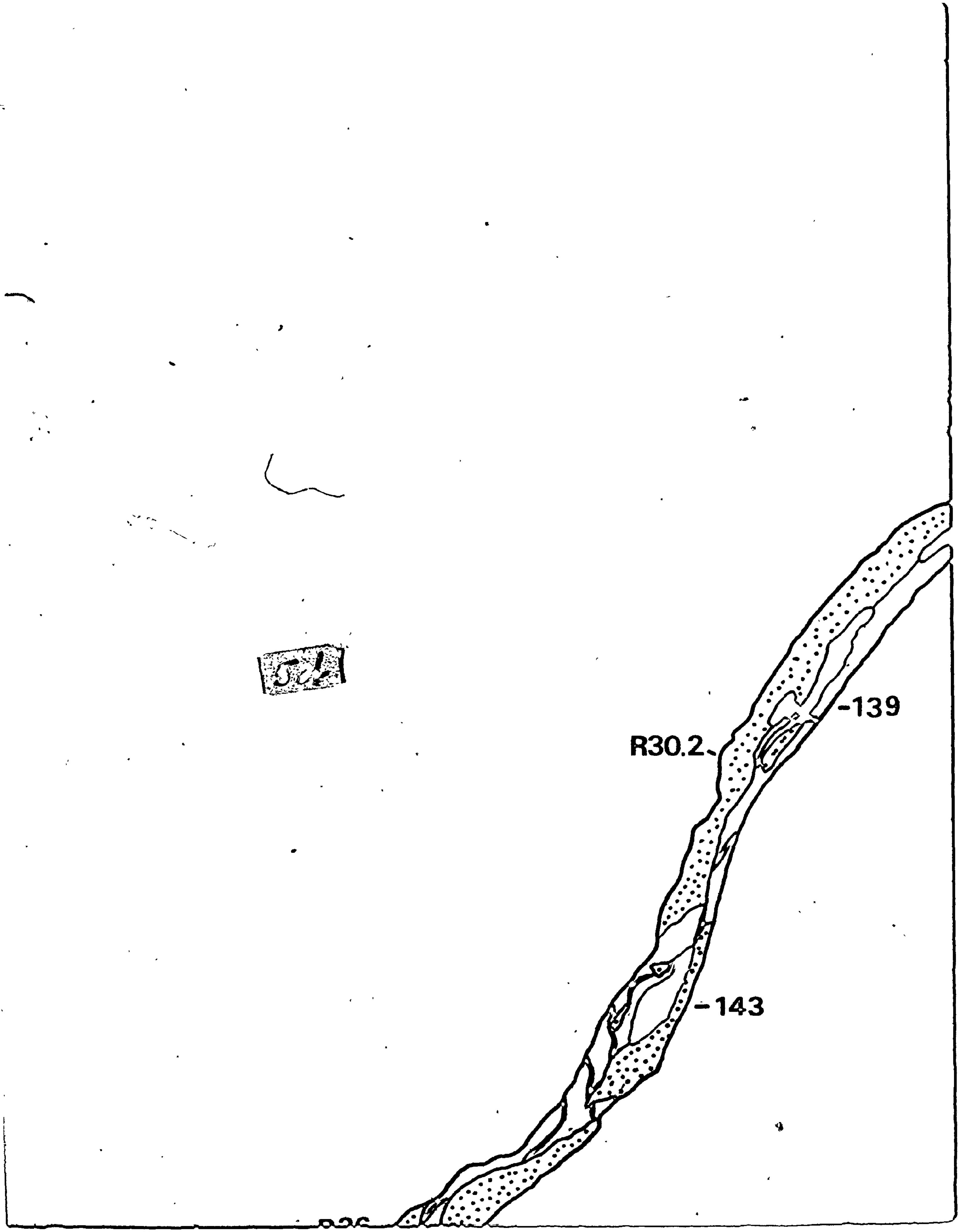
1 of 1

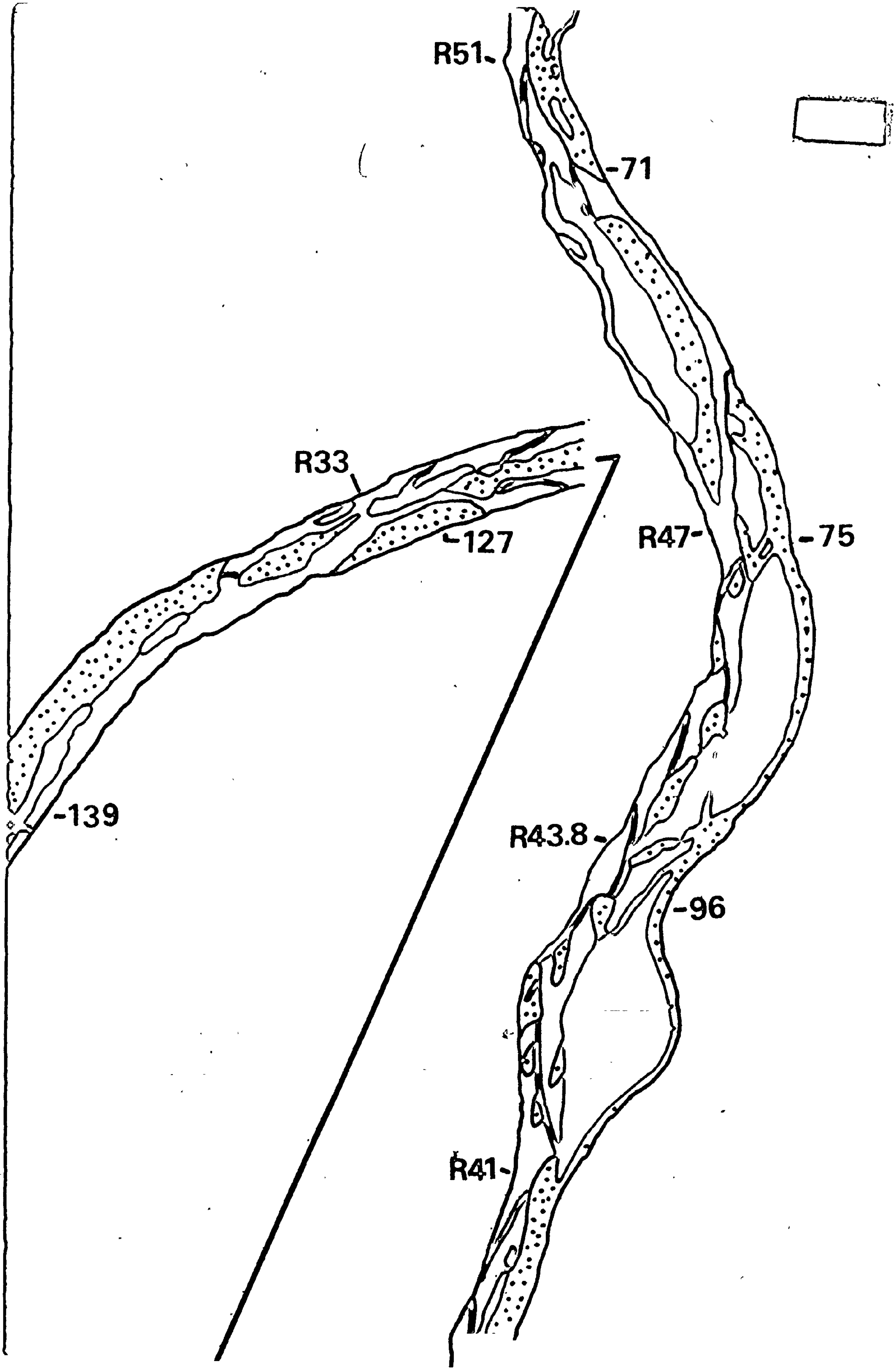


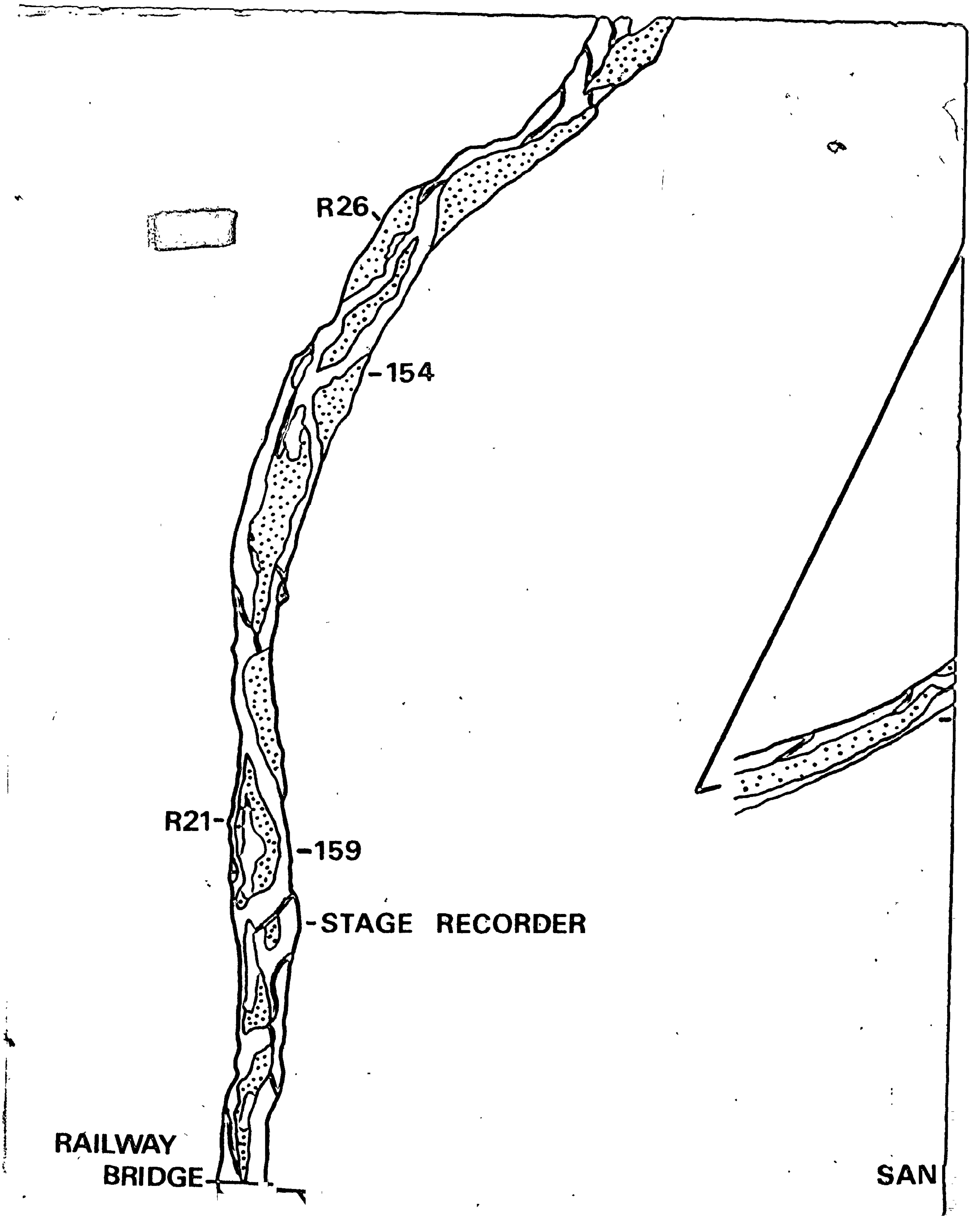

SASKATOON
R71.5
-32
R70
-40
-43
MOON
LAKE
R62.2
R64.5

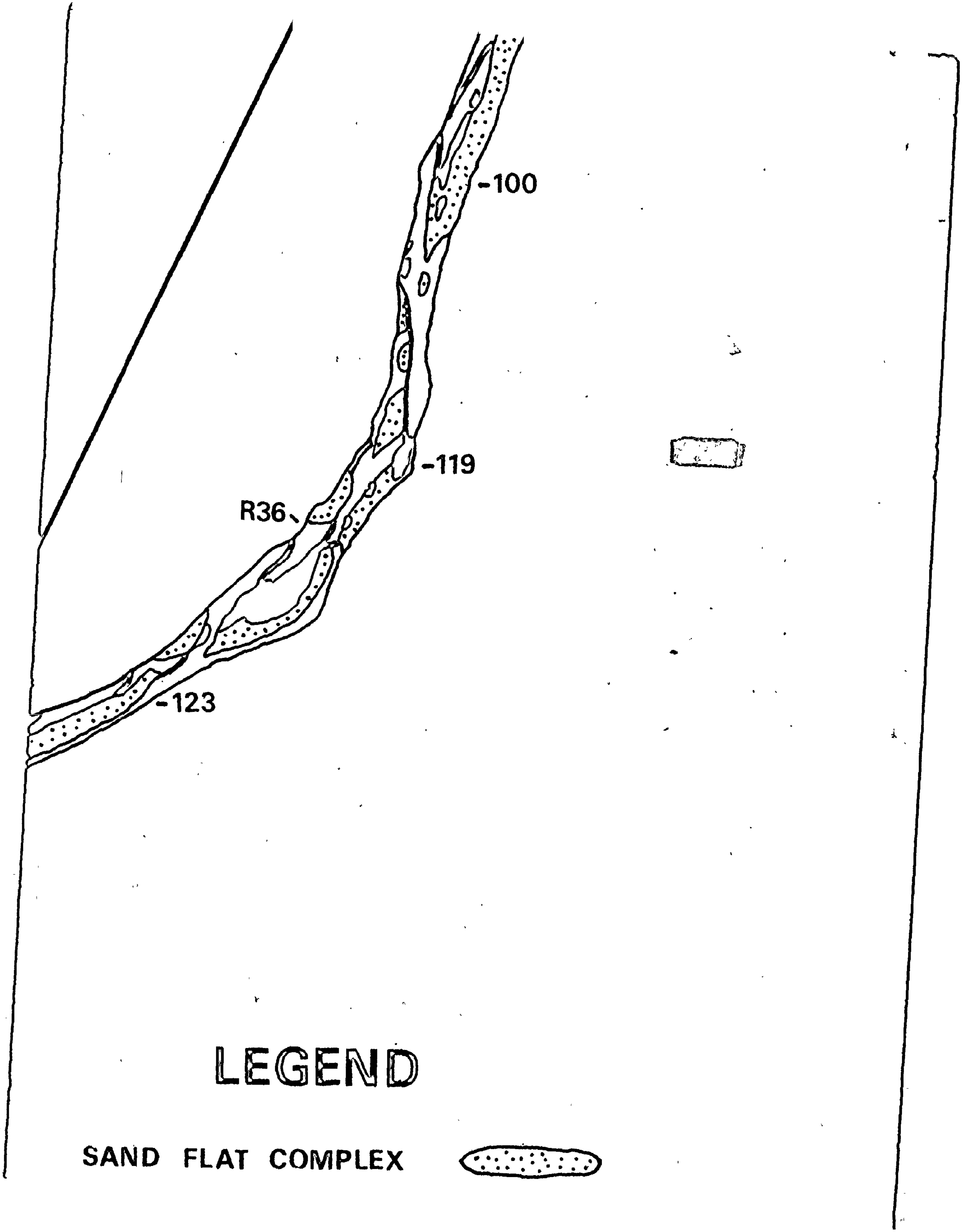

3 of
R59
5 KM
PIKE
LAKE

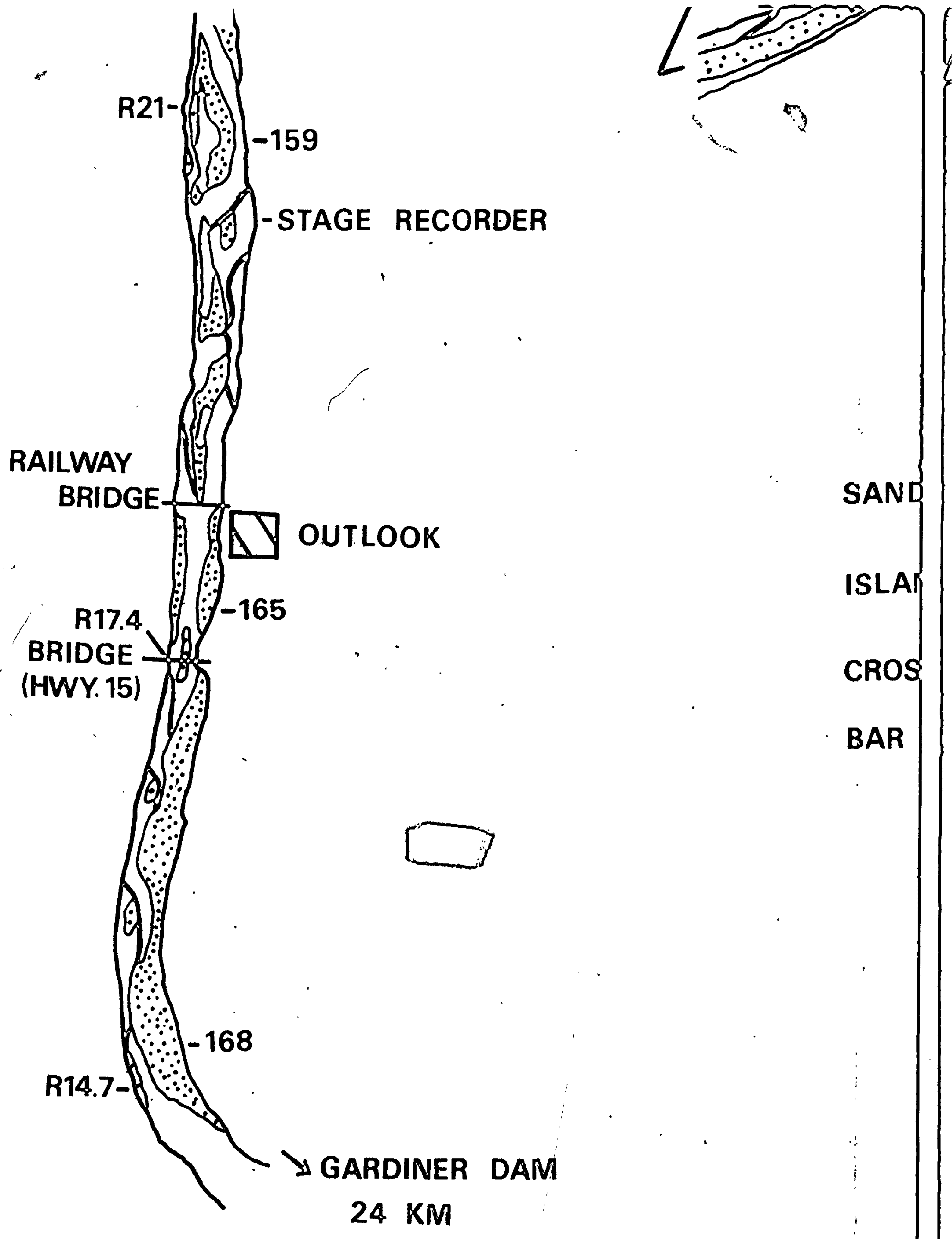

R62.2
R64.5
R63.3
-53
-50
R59.1
-60
R55.5
-81
R54
PIKE
LAKE
-68
R51

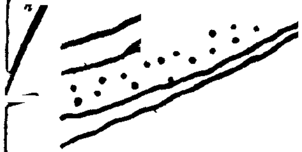

-139
R30.2
-143


R51
-71
R33
-127
R47
-75
-139
R43.8
-96
R41

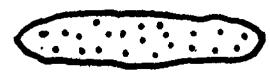

R26
-154
R21
-159
-STAGE RECORDER
RAILWAY
BRIDGE
SAN


100
119
R36
123
LEGEND
SAND FLAT COMPLEX


R21
159
STAGE RECORDER
RAILWAY BRIDGE
OUTLOOK
165
R17.4
BRIDGE (HWY. 15)
168
R14.7
GARDINER DAM 24 KM
SAND
ISLA
CROS
BAR



LEGEND

SAND FLAT COMPLEX 

ISLAND 

CROSS CHANNEL BAR
OR
BAR SYSTEM