Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada

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ABSTRACT

The South Saskatchewan River has a long term average discharge of 275 m³/sec, with flood peaks in the range of 1500 to 3800 m³/sec. South of Saskatoon, the four major types of geomorphological elements recognised are channels, slipface-bounded bars, sand flats and vegetated islands and floodplains. Major channels are 3–5 m deep, up to 200 m wide, and flow around sand flats which are 50–2000 m long, and around vegetated islands up to 1 km long. At areas of flow expansion, long straight-crested cross-channel bars form. During falling stage, a small part of the crest of the cross-channel bar may become emergent, and act as a nucleus for downstream and lateral growth of a new sand flat.

The dominant channel bedforms are dunes, which deposit trough cross bedding. Cross-channel bars deposit large sets of planar tabular cross bedding. Sand flats that grow from a nucleus on a cross-channel bar are mostly composed of smaller planar tabular sets, with some parallel lamination, trough cross-bedding, and ripple cross-lamination. A typical facies sequence related to sand flat growth would consist of in-channel trough cross-bedding, overlain by a large (1–2 m) planar tabular set (cross-channel bar), overlain in turn by a complex association mostly of small planar tabular cross-beds, trough cross-beds and ripple cross-lamination.

By contrast, a second stratigraphic sequence can be proposed, related only to channel aggradation. It would consist dominantly of trough cross-beds, decreasing in scale upward, and possible interrupted by isolated sets of planar tabular cross-bedding if a cross-channel bar formed, but failed to grow into a sand flat. During final filling of the channel, ripple cross-lamination and thin clay layers may be deposited. In the S. Saskatchewan, these sequences are a minimum of 5 m thick, and are overlain by 0.5–1 m of silty and muddy vertical accretion deposits.

INTRODUCTION AND DEFINITIONS

As a result of extensive work on sandy meandering fluvial systems, the relationships between geomorphological elements, stratification and depositional facies sequences are reasonably well understood. The geomorphological elements include the channel, point bars, levees, and floodbasins, and the stratification results both from the migration of bed forms and by vertical deposition on the floodplain. Facies sequences are

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known both from modern and ancient systems, and comparison of these facies sequences has led to the development of a facies model for meandering systems (e.g., Allen, 1965, 1970; Jackson, 1976). The model emphasizes a fining-upward sequence formed essentially by lateral accretion (point bar and in-channel deposits) and vertical accretion (flood stage overbank deposition on the floodplain).

By comparison, the relationships between geomorphological elements, stratification, and depositional facies sequences have received little study in sandy braided systems: these relationships are the main point of this paper. Previous work includes studies of the Durance and Ardèche (Doeglas, 1962), Brahmaputra (Coleman, 1969), Platte (N. D. Smith, 1970) and Tana (Collinson, 1970) Rivers. There is little agreement concerning nomenclature of the geomorphological elements in these rivers, because of their complexity, and the fact that different features are observed in different stages of growth and destruction. We will use the term 'bar' to refer to long, low, slipface-bounded features that occur on a scale larger than that of individual bedforms (ripples, sand waves, dunes). In scale, orientation and morphology, our bars are similar to the linguoid and transverse bars of Miall (1977, p. 14), and to the transverse bars of Ore (1963) and Smith (1970). Most of the bars are 'unit' bars (Smith, 1974, p. 210) in that they are 'relatively unmodified' with 'morphologies determined by mainly depositional processes'.

We use the term 'sand flat' for larger areas of sand accumulation that are emergent at low to moderate river stage (Figs 3, 4, 6). Sand flats can be relatively simple (exposed top of cross-channel bar in Fig. 4) or very complex (Fig. 6); the term braid bar has not been used to avoid confusion with the slipface-bounded bars defined above.

No schemes for the origin, growth and preservation of these large sand flats have been proposed in the literature, although they are likely to be preserved in the geological record. Unfortunately, there are few accounts of ancient braided (or low sinuosity) sandy systems. In the Devonian of Spitsbergen, Moody-Stewart (1966) interpreted some sandstones as low sinuosity stream deposits, and braided stream sandstones have been described from the Van Horn Sandstone of Texas (McGowan & Groat, 1971). More recently, facies sequences have been described from the Devonian Battery Point Sandstone in Quebec (Cant & Walker, 1976), and the geometry of the sandy braided Westwater Canyon Member, Morrison Formation, New Mexico, has been described by Campbell (1976). Palaeocurrent variability has been emphasized by Miall (1976) in his study of the Cretaceous Isachsen Formation, Arctic Canada.

Our purpose in this paper is to identify the main geomorphological features of the modern South Saskatchewan River, in a braided reach about 60 km south of Saskatoon, Saskatchewan (Fig. 1). Bar and sand flat growth, development and destruction has been monitored from government air photos, our own low level flying, and three seasons of mapping, trenching and box coring, echo sounding, and hydrodynamic measurement. We will show that the large sand flats develop through a series of recognizable stages, and that this development gives rise to predictable facies and stratification sequences that can be recognized in the geological record.

Some further definitions are necessary. We shall use the term 'river' for the entire braided complex between banks, thus the river in Fig. 3 is about 600 m wide and its local trend is almost due north. Channels are actual topographic depressions in the river bed. Their dimensions therefore depend on the configuration of the river bed, not on flow widths and depths which vary with river stage.
THE SOUTH SASKATCHEWAN RIVER

This river is the largest in the southern Canadian Prairies (Fig. 1). Its headwaters are in the Rocky Mountains, and it flows into the sea in Hudson Bay. The long term average discharge is 275 m$^3$/sec (records span 1912–present), but mean and maximum discharges vary considerably year to year (Fig. 2). The average monthly discharges also vary considerably, with maximum flow occurring most years in June following snowmelt in the Rocky Mountains and increased precipitation throughout the drainage basin. The river is frozen over during the winter, although water released from the Gardiner Dam flows in channels under the winter ice (Fig. 2, inset). The Gardiner Dam is about 25 km upstream from the study reach, and was completed in 1967. The effect of the dam has been to reduce the peak June flows and to increase the winter discharge. Suspended sediment now settles in the reservoir, and concentrations in the study reach have been reduced by 80%. Mean concentrations have fallen from about 0.43 to 0.08 g/litre, and at bankfull flow, they have dropped from 1.5 to 0.3 g/litre (Water Resources Branch, Environment Canada and Saskatchewan Department of Natural Resources, 1969–74). The water is now so clear that channel floors can be readily seen through about 3 m of water. In order to check that no major downcutting has taken place since the dam was closed, we have used the repeated surveys of the river bed by the Water Resources Branch of Environment Canada, and the Saskatchewan Department of the Environment (1969–74). We calculate that the maximum lowering of the bed averaged over the study reach is about 0.2 m, which is much less than local fluctuations due to channel shifting. Also, a comparison of air photos flown before and after the dam shows that the scale and type of active bars and sand flats has not changed. Sand is presently being supplied by abundant fluvial and aeolian deposits in the valley just downstream of the dam.
In the study reach, the river flows northward with an average slope of 0.0003. The river valley averages about 1 km wide, and is incised about 30 m into flat lying Cretaceous sandy shales. Within the valley the river is braided, with the channels and sand flats occupying most of the valley floor. Small floodplains up to 100 m wide are present in places, adjacent to the valley wall. The valley is straight to irregularly curving (Fig. 1), but about 25 km south of Saskatoon, it widens and the river swings into very irregular meanders (sinuosity 1.8). Bars and sand flats are still present in the channel, giving a braided-within-meandering pattern.

The bed material is a moderately well sorted sand, mean diameter 0.3 mm. In some channels, a small proportion of gravel (up to 2 cm) is present.

GEOMORPHOLOGICAL ELEMENTS

The major geomorphological elements, on a scale larger than individual bedforms, have been identified from government air photos (Fig. 3), our own low level flying, and mapping in the river valley. They consist of channels, slipface-bounded bars, sand flats, and vegetated islands and floodplains.

Channels

At any one locality there are commonly one or two major channels, and several minor channels. The major channels average about 3 m (maximum 5 m) in depth below the level of adjacent sand flats, and widths vary from about 70 to 200 m. The major channels trend almost parallel to the river (as defined above), but they curve in places and cross the system diagonally. Analysis of thirty air photos showed that the average deviation of the major channels from the trend of the river is about $13^\circ$, and that 90% of the channels deviate less than $30^\circ$. 

Fig. 2. Discharge records, 1912–1975. Inset, note the low winter flow and peak June flows before the dam was closed, and the more even discharge since the closure in 1967. The post-dam average monthly discharges mask the flood peaks, which in 1969 and 1975 were about 1800 $m^3/sec$.
Velocity profiles were measured at many localities using a Price-type AA current meter. Mean flows were calculated by averaging velocities at 0.2 and 0.8 of the depth, except at very high flows when only surface velocities could be measured. Under these circumstances, the mean was taken as 0.91 times the surface velocity (Toffaleti, 1963).

In the centres of major channels, mean velocities are in the range 0.75–1.75 m/sec, depending on river stage. Bedload is transported through these channels at all stages, and at high stages, large amounts of fine sand are also transported in suspension.

The beds of the major channels are covered by sinuous-crested dunes at all but the very lowest stages. Echo sounding has shown that the deeper channels have larger dunes. Maximum dune height of 1.5 m was observed during the 1975 flood stage (Fig. 2), in a mean flow depth of 3.0 m, and mean velocity of 1.75 m/sec. (Froude number, 0.35).

Along many of the more gently sloping margins of the major channels, long, low bedforms similar to lower flow regime sand waves (terminology of Southard, in Harms et al., 1975) are common. The wavelength of such sand waves is up to 10 m, and height is up to 0.3 m. Also, within some of the shallower parts of the major channels, there are regularly spaced (repetitive) linguoid bars (Collinson, 1970), but for reasons not yet understood, these are relatively rare in the S. Saskatchewan compared with the Tana River (Collinson, 1970). Most of the larger, non-repetitive bars with slipfaces in the S. Saskatchewan are straight to curving in plan view, and are attached at one or both ends to sand flats, vegetated islands, or the river banks. They will be discussed below.

Minor channels range in depth up to 1.0 m, and may be up to 125 m wide. Their directions are much more variable than the major channels, and their average deviation from the river trend is about 30°. Mean velocities are mostly less than 1 m/sec.
except at flood stage, and because the minor channels are in topographically higher parts of the system, they are greatly affected by river stage. Flow and sediment transport tend to be intermittent. The most common bed forms are long, low sand waves and current ripples, but at periods of higher flow, sinuous crested dunes up to 0.3 m high may be present.

Bars

Slipface-bounded bars are common in the S. Saskatchewan, occurring within channels and on top of sand flats. They are normally non-repetitive forms controlled by pre-existing topographic variations (Cant, 1976). They typically occur in areas of flow expansion, commonly at channel junctions or places where channels widen (Figs 3 and 7). Some bars form in similar positions in the Platte River (Smith, 1970).

The non-repetitive bars in the S. Saskatchewan do not appear to be equilibrium bed forms, in the sense that ripples, sand waves and dunes are. Bars persist through long periods of widely varying flow, during which ripples, sand waves and dunes, or upper flow regime plane bed may be developed upon them. We emphasize that the main factor controlling their initial formation is flow expansion, controlled by the position of pre-existing channels, banks and islands.

Bars range in height from about 0.15 to 2.5 m. The smaller bars occur on top of, or on the margins of sand flats, and may be only a few tens of metres long. Larger bars extend hundreds of metres diagonally across major channels (Figs 4 and 5). In their simplest form, these large bars are relatively straight with the highest point along the crest line near the centre. They extend between major topographic elements in the river, linking sand flats to one another, or to vegetated islands, or to the main river banks. These are major features in the S. Saskatchewan, and are here termed 'cross-channel bars' (Figs 3 and 4). They range in height from 0.3 to 2.5 m, depending on the depth of channel in which they form. During falling stage, sand flats of varying size and complexity become exposed along the bar top. They essentially divide the one cross-channel bar into a series of smaller bars at low stage, and the entire assemblage is termed a 'bar system' (Fig. 4).

Because of the relatively straight crests of the slipface-bounded bars, the predicted internal sedimentary structure would be a planar-tabular set of cross-bedding. This was confirmed by all of our trenches and box cores, and similar planar cross-beds were reported by Collinson (1970) and Smith (1970, 1972).

Sand flats

Sand flats (Figs 3, 4 and 6) range from 50 m to 2 km in length, and 30 to 450 m in width. Air photos and ground observations show that they are complexes of smaller features, and because of their morphological irregularity (Fig. 3) they resemble the exposed areas of sand in the Tana River (modified linguoid bars, or side bars of Collinson, 1970, figs 3-8). The S. Saskatchewan sand flats are also similar to the immense areas of sand in the Brahmaputra (Coleman, 1970) and Ganges (Morgan, 1970) Rivers.

The sand flats are submerged when the river discharge exceeds 230 m³/sec. During the month-long flood of 1975 (Fig. 2, maximum 3 day discharge 1812 m³/sec) water depth over the sand flats was about 1 m, with an average velocity of 1.3 m/sec (Froude number, 0.42). Immediately after recession of the flood, the most abundant features on
the sand flats were bars of various heights, ripples and sandwaves. Small areas of sinuous crested dunes and horizontal lamination with parting lineation were also present. After several weeks of exposure to sun and wind, the sediment dried out to depths of 0.1 to 0.2 m, and was wind-deflated. Aeolian dunes up to 0.4 m high were formed in a few places.

Many of the sand flats are traversed by minor channels up to 0.4 m deep, with ripples and sand waves on their beds. These occur in low areas on the flats, concentrating falling-stage flow after emergence of most of the flat. In some parts of the river, there are many adjacent sand flats, separated only by minor channels (Fig. 6). These areas of interconnected sand flats are termed ‘sand flat complexes’, and may have formed in one of three ways. First, a very large flat may have been dissected by minor, falling stage channels. Second, many smaller flats may have grown independently, and became connected by deposition in the intervening channels. Third, the presence of one large flat may have protected depositional areas downstream and promoted deposition there. The sand flat complexes appear to have evolved through several periods
Fig. 5. Cross-channel bar (C-C.B.) with nucleus (N₁) and 'horns', shown by arrows that also indicate direction of flow and sand transport. A second nucleus (N₂) has emerged but has not yet developed horns.

Fig. 6. Large sand flat complex dissected by many minor channels. The major channel flowing around it is narrow and deep until the area of flow expansion, where a large diagonal cross-channel bar (C-C.B) with emergent nucleus has formed. The minor channel M.C. has smaller examples of nuclei with horns, upstream and downstream of the letters M.C. Linguoid bars (L) are present in the major channel. Flow to northeast. Original photo supplied by the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Canada.
of deposition and erosion, with one or more of the above processes operating at
different times.

Vegetated islands and floodplains

These features occur at many places in the study reach, but have no detectable
patterns of spacing or distribution (Fig. 3). The flood plains are restricted in area
because of the narrow valley, and commonly occupy erosional re-entrants into the
valley walls. Most islands are elongated parallel to the river direction, and are up to
1 km long. Islands that are separated from floodplains only by narrow channels are
probably erosional remnants of the floodplain. Islands and floodplains stand about
1–2 m above the level of the sand flats, and are covered with grasses, bushes and, in
places, large trees. The vegetation stabilizes the islands, and in many cases little change
can be seen on air photos taken 15 years apart.

In places where sand flats are immediately adjacent to vegetated islands without
intervening channels, sand from the flats is blown onto the islands, trapped by the
vegetation, and accumulates in aeolian dunes up to 2 m high.

RELATIONSHIP OF CHANNELS, BARS, AND SAND FLATS

Viewed on a larger scale, the braided reach consists of one or two major channels
flowing around and between sand flats and sand flat complexes (Figs 6, 7 and 8). In
areas where the sand flat complexes are wide (Fig. 7, A), the major channel is narrow
and relatively deep. Where the cross-sectional area of the channel increases at bends
(Fig. 7, B) or at the downstream ends of sand flat complexes (Fig. 7, C, F), cross-
channel bars are formed. The direction of advance of the cross-channel bars is com-
monly oblique to the channels and the river. Measurement of the orientation of fifty
of the largest bars shows an average deviation of 69° from the local river trend (Fig.
7F). Over the bar, the channel is wide and shallow and at low stage may split into
a series of smaller channels separated by sand flats (Fig. 7, C) giving rise to a bar
system.

Downstream, the flow is commonly constricted again by islands, sand flats and
river banks. Thus, the system of a narrow, deep channel that widens and shallows
downstream, spawning a cross-channel bar, is repeated (Fig. 7, D). There is little
regularity to the spacing or direction of the cross-channel bars. The spacing varies in

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Fig. 7. Diagrammatic simplification of a typical reach, flow to right, showing only the major channels
flowing between sand flats (stippled). Bar systems are shown in areas of flow expansion, the lines
indicating the bar slipface, and the black areas indicating emergent nuclei and new, small sand flats.
The average deviation of flow over the bar systems compared with the river trend is 69°. Letters are
explained in the text. River valley width about 1 km.
the downstream direction between 1 and 3 km, and the directions of divergence of successive bars may be the same (Fig. 7, C and E) or opposite (Fig. 7, B and C).

Viewed on the scale of individual channels, there are also slightly narrower, deeper reaches, and slightly wider shallower reaches (Fig. 8) in which oblique cross-channel bars form. These deeper and shallower reaches are similar to pool and riffle sequences, except that typical pool and riffle sequences (Leopold, Wolman & Miller, 1964) have a regular or quasi-periodic spacing, whereas those in the S. Saskatchewan appear irregular or random. The apparently irregular distribution of deeper reaches and wider shallower reaches is partly due to the development of many small bars at low river stage, partly to various degrees of dissection of cross-channel bars, and partly to the growth of some cross-channel bars into sand flats. Thus the deep-to-shallow downstream trends in the S. Saskatchewan more closely resemble the pool and bar sequences described by Smith (1973) in pebbly braided streams.

Fig. 8. Major channels (shown by small arrows) flowing around a sand flat complex dissected by minor channels, S and D indicate alternating shallower and deeper areas in the major channels. Note nucleus with downstream elongated horns above the 100 m scale. Original photo supplied by the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Canada.

CHANNEL SHIFTING

Comparison of 1967 and 1971 air photos shows that considerable channel shifting occurred during these four years. During our field work, it became apparent that the channels either migrated laterally, or aggraded in one reach and simultaneously degraded in a nearby reach. Lateral migration of major channels resulted in complete destruction of sand flats, but migration of the shallower minor channels only resulted in the reworking of the uppermost sand flat deposits (see Fig. 15).

Processes of aggradation and degradation were observed during the 1975 flood, when one major channel aggraded between 0.5 and 1.0 m, mostly by deposition of sediment from migrating dunes without the development of bars or sand flats. During
aggradation, flow gradually increased in an adjacent, wider reach. A similar mechanism of aggradation and flow diversion was described by Chien (1961) in the Yellow River of China, and possible resulting stratigraphic sequences are discussed later and illustrated in Fig. 15.

**INITIATION OF SAND FLATS**

In sandy systems, braid bars are commonly accepted as ‘being there’, with little or no documentation of their origin and development. It is not even clear whether they originate from a coarse lag, as is the case for braid bars in gravelly systems (Leopold & Wolman, 1957; Hein & Walker, 1977). In the absence of any understanding of their evolution, it is difficult or impossible to propose typical sequences of sedimentary structures for large sand flats. By contrast, the internal structures of point bars in meandering systems are fairly well known. In this section of the paper, we emphasize and document a sand flat developmental sequence; the large sand flats in the S. Saskatchewan appear ‘to originate from small sandy areas newly emergent on the tops of cross-channel bars (Figs 4 and 5). In fact, most of the sand flats less than 150 m long appear to be relatively newly formed, ‘unit bars’ in the sense of Smith (1974). This is suggested by the appearance of new sand flats during the field work, and by the fact that small sand flats on the 1974 air photos are not detectable on the 1971 air photos. Photos and ground surveys also showed that many small sand flats were destroyed by the 1974 and 1975 floods.

Although the small sand flats have variable morphologies, they can be considered in terms of three end members, symmetrical and asymmetrical mid-channel flats, and side flats (Fig. 9). They form by the emergence of part of a cross-channel bar during falling stage. The location and orientation of the cross-channel bars, and the position of the high point along the crest line, controls the initial type of new sand flat. Our observations of these early stages of sand flat formation include repeated mapping of several bars, and comparison and analysis of morphologies of bars and small flats seen on government air photos, and from our own low level flying.

**Initiation of symmetrical flats**

The development of a symmetrical flat will be discussed in detail; the other types evolve in an analogous manner. The flat first develops on the crest of a straight or gently curved, slightly submerged, cross-channel bar which is more or less perpendicular to the flow and the channel margins (Fig. 9-1). Flow is spread almost evenly across the bar, and sediment is transported to the bar crest as bedforms, typically ripples, sand waves or sinuous crested dunes. As the stage falls, that part of the bar front which is slightly higher experiences reduced sediment transport, and becomes emergent (Figs 9-2 and 10). The small emergent area is here termed the ‘nucleus’, two of them can be seen at the left end (facing downstream) of the bar system in Fig. 4, and excellent examples can also be seen in Figs 5, 6 and 8.

As flow continues, sediment is swept around the nucleus, and expanding flow around the downstream end results in inwardly directed sediment transport (Fig. 9-3). The bar continues to grow, but with two lobes that resemble downstream-lengthening ‘horns’ on the sand flat, each horn having an inwardly facing slipface (Fig. 10). This
sequence of events was directly observed in one locality, and all stages of development, from a tiny exposed nucleus to a nucleus with long downstream horns, have been identified on various air photos.

Small asymmetrical flats form in an exactly analogous way, except that they originate on diagonal cross-channel bars (Fig. 9-2A). The original diagonal orientation of the bar is probably a response at least partly to higher rates of sediment transport on one side of the channel compared with the other (south side in Fig. 9-2A); consequently, one horn tends to lengthen faster than the other, emphasizing the asymmetry of the sand flat. Side flats (Fig. 9-2S) develop in curving channels where the high point of the cross-channel bar was close to a stable bank. As the side flat lengthens, its single horn has a slip face directed toward the channel bank. Thus a small side flat resembles the scroll bars of meandering rivers (Sundborg, 1956; Jackson, 1976), except that it is physically and genetically linked to the original cross-channel bar.

**SUBSEQUENT GROWTH OF SAND FLATS**

Air photos of sand flats show all sizes and morphological gradations between the nucleus with horns (Fig. 5) and complex 2 km long sand flats (Fig. 6). We propose that by accretion and modification, some nuclei with horns may grow into large flats;
many other nuclei in varying stages of development are destroyed by subsequent floods. The processes described below were investigated by repeated mapping of sand flats, and by re-mapping or re-photographing flats after flood events, as well as using complete stage recorder data and current velocity measurements (Cant, 1976). We emphasize that the subsequent growth is more complex than the initiation, and that any or all of the following processes may occur in various combinations.

**Sideways and downstream accretion**

The small sand flat that has developed from a nucleus within a channel now acts as an obstacle to flow. During falling stage, flow expansion around the widest part of the sand flat or around its downstream margin may result in the formation of bars up to about 0.75 m high. These are driven diagonally out of the channel and inward toward the sand flat, somewhat like a second or later generation of horns (Fig. 11). As the stage falls further, the crests of these later generation bars become emergent, and a quiet slough (muddy backwater) is created where fines and organic debris commonly settle. These bars lengthen as the stage falls because flow is diverted farther and farther around the downstream end before flow expansion can take place (Fig. 12). Sediment is carried farther downstream before it can avalanche over the slipface, causing both downstream lengthening and inward growth by slipface avalanching (Fig. 9-4A). The addition of sediment to the margins of the small sand flat in this way causes both an aggradation and widening of the sand flat, as well as downstream lengthening (Fig. 11).
Fig. 11. Sand flat (with flow to left) which has lengthened downstream, and shows at least three generations of bars (arrowed) being driven laterally from the side channel. The bar farthest upstream appears to have been driven up onto the nucleus (N), and has swung around on both sides due to higher rates of sediment transport in the side channels. Most of the individual bedforms visible are straight-crested to somewhat diamond-shaped sandwaves.
Fig. 12. A more complex sand flat that shows a small dissection channel cutting diagonally across it (towards the camera). This channel has been partly infilled by migration of bars within it. Higher parts of the sand flat show bars which were deposited during a period of increased discharge. A bar building toward the near side of the sand flat is causing the sand flat to accrete laterally and is trapping a deep slough between itself and the sand flat.
Where a low, straight crested bar approaches a small sand flat from upstream, a similar result takes place. The bar is driven part way up onto the back of the nucleus, but with higher rates of sediment transport in the flanking channels, the bar crest becomes curved (Figs 9-4B and 11). Once past the position of the original nucleus, flow expansion deflects these bars even more, driving them inward in the manner discussed above. Thus, the inward-driven bars may originate independently of the sand flat, in a position upstream, or they may form by flow expansion in the channel adjacent to the sand flat. If bars are driven up more or less symmetrically from both sides, a slough will develop between them at low stage which will trap fine suspended sediment and organic material (Figs 11 and 12).

**Vertical aggradation**

Most vertical aggradation takes place during periods of high to flood stage discharge, when bars up to 1 m high are driven up onto the sand flats and deposit planar tabular cross-beds. During the flood of 1975 (1812 m$^3$/sec), the flow over the sand flats was about 1 m deep and averaged 1.3 m/sec. Consequently, the flow was not deflected much by local topographic variations on the sand flats, and the bars tended to have straight to slightly curved crest lines oriented essentially perpendicular to the river trend. This flood also deposited 0.4 m of parallel laminated sand on some flats, with a parting lineation (subsequently etched out by wind deflation) that also paralleled the river trend. The smaller flood of 1974 (850 m$^3$/sec) was much more influenced by local topographic variations on the tops of the sand flats, and the bars had much more irregular crestlines, and more variable orientations with respect to the river trend. Some of the bars had the shape of small symmetrical sand flats (Fig. 9-3), but represented only the reworking or aggradation of an existing sand flat. The original symmetrical sand flats develop from cross channel bars that themselves rest upon channel deposits.

As well as bars, sand waves (Fig. 11) and (locally) sinuous crested dunes occur on top of aggrading sand flats. The abundant ripples seen on the sand flats when they become exposed are a late stage modification by falling flood stage, they do not transport much sand from the channels up onto the flats during the flood stage.

Bars which migrate onto sand flats from a channel upstream (Fig. 9-4B) rest mostly on the sand flat and contribute to its vertical accretion (Fig. 11). Part of the bar, however, may still rest upon pre-existing channel deposits, thus causing upstream and vertical growth of the sand flat. This process only occurs at high river stages and affects relatively few sand flats: thus upstream accretion of flats is probably a volumetrically minor process within the river.

The bars that are driven onto the sand flats, either from upstream, or from channels adjacent to the sand flats, are covered by smaller bedforms that actually transport the sediment to the bar crest. In shallower water, these bedforms are commonly straight crested or rhomboid sand waves, but in deeper water, the normal bedform is dunes (Fig. 9-4A).

In the case of side flats, all of the bars driven up onto the flats face the river bank. None of them builds right up to the bank, because a channel is formed there that drains the flow after it has passed over the bars, thus preventing further advance of the bar front. At low stages, these channels become quiet sloughs that fill with suspended fines and organic material; at slightly higher stages flow down the slough.
(or minor channel) develops sand waves and deposits small sets of planar tabular cross bedding.

**Linking separate sand flats**

Comparison of sand flat morphology before and after the 1975 flood suggests that in at least two places, sand flats originally separated by channels became linked by the development of large bars at the downstream ends of the channels. The bars developed at high stage, in a flow about 1 m deep, and built up to the same height as the sand flats. When the stage fell, the flats and bars became emergent and the channels were completely blocked. The origin of the channels is unknown; they may have separated two totally different sand flats, or they could have been channels that dissected pre-existing sand flats.

**Erosional modification**

The larger sand flats can be drastically modified by erosion at flood stages. Typically, erosion creates a channel (Fig. 12) or a number of minor channels (Fig. 6) that dissect a large flat into a series of smaller flats. The channels are normally less than 1 m deep, and are incised into sand flat deposits (see block diagram, Fig. 14). Subsequent deposition within these minor channels can link the sand flats together again, as discussed above.

In other places, major channels may shift laterally, forming steep erosional banks on sand flats or vegetated islands, thereby drastically altering both the surface morphology and ultimate lateral facies associations of the channel and sand flat. Flats may also suffer degradation during flood stage, particularly at their upstream ends. Several were monitored by driving in wooden stakes and measuring depth of erosion; the maximum net erosion during the period September 1974–May 1975 was 0.5 m, eroded from one sand flat.

In the most drastic cases, the near-total erosion of a small sand flat leaves behind only a small, submerged higher area in a channel. This higher area can be rebuilt into a sand flat by lateral, downstream and vertical accretion, or it may subsequently be overridden by a cross-channel bar, and hence localize the development of a nucleus and perhaps a completely new sand flat.

**Sand flats: summary of initiation and growth**

The development of a nucleus on a cross-channel bar, and the early downstream lengthening by the growth of ‘horns’ (Fig. 5) is a fairly simple and predictable process. The growth of this new small sand flat into a large, complex flat that may be preserved in the geological record is by no means simple or predictable. It involves aggradation, by driving several later generations of bars onto the sand flat from upstream or from adjacent channels (Figs 10, 11 and 12). It involves erosion, either by trimming the sides of the flats, or by cutting minor channels during flood stage, probably as the flood wanes (Fig. 12); and it involves the linking of separate sand flats by deposition in intervening channels. With these processes in mind, however, the stratification produced by individual bedforms and bars can be understood in context, and used as a basis for models of braided stream sand flats.
STRATIFICATION

Channels

All echo-sounder records taken in major channels (Cant, 1976) show sinuous-crested dunes with slip faces directed essentially down-channel. Dunes tend to be larger in the deeper channels, and it is predicted that within one sequence of channel deposits, the trough cross-bedding would decrease in scale upward (Fig. 15). In the shallower (<0.8 m) channels where box-coring was possible, trough cross bedding was abundant with individual sets averaging about 0.1 m thick.

Box-coring and trenching in the cross channel bars invariably revealed large solitary sets of planar tabular cross bedding, resulting from the migration of the cross-channel bars. These bars are commonly oblique to the river trend (Fig. 7), and hence, the palaeocurrent directions of the large planar tabular sets are at high angles to the directions of the trough cross-beds immediately below.

In major channels that have been persistently aggrading, box coring showed that the large trough cross-beds are overlain by small planar tabular sets, and cosets of ripple cross-lamination. By sieving, it has also been shown that the sediment in the deeper channels is only a little coarser than that in shallower ones; typically the modal size decreases from about 1.5 to 2.0φ (0.35–0.25 mm). There is consequently little development of fining-upward sequences within the channel deposits, although in the bases of many channels there is a lag of mud intraclasts and pebbles.

Sand flats

Data on sand flat stratification has been accumulated by trenching to the water table (average about 0.5 m), by box coring on the margins of sand flats, by observation of processes operating (particularly at flood stages), by inferences from the morphology and origin of small flats, and by study of stratigraphic sections in the river banks believed to represent older sand flats (Fig. 13).

Newly formed sand flats represent the emergent tops of cross-channel bars. Hence, the large (0.5 to 2 m) planar tabular cross-bed set (Fig. 15), commonly at a high angle to the river trend, is fundamental to all subsequent growth of the sand flats. Above this large planar tabular set, trenching and box coring demonstrate that the sand flats are dominated by smaller planar tabular sets (0.3–0.5 m). These represent bars driven from the channels onto the flats during lateral and downstream accretion. Directions of dip of the foresets are very variable. Near the margins of the sand flats, dips are commonly at high angles to the river trend, inward toward the centre of the sand flat (Figs 9-4A, downstream end; 11). Bars of this type were associated with the relatively small 1974 flood. By contrast, the larger 1975 flood formed bars on the central, higher parts of the sand flats which faced directly downstream, giving planar tabular cross-beds with a palaeoflow parallel to that of the river (Fig. 9-4A, upstream end). In the faces exposed in the river banks, the planar tabular cross-beds were commonly interrupted by reactivation surfaces, indicating changes of stage during bar migration.

Although the bar deposits make up volumetrically the greater part of the sand flat, other stratification is also present. Sets of parallel lamination up to 0.4 m thick may be deposited during flood stages, and in the upper parts of the sand flats, small
Fig. 13. Sequence of structures exposed in river bank, showing small-scale trough cross-bedding (lower half of photo), ripple- and ripple-drift cross-lamination, a 30 cm planar tabular set, and finally silty and muddy vertical accretion deposits with roots of present floodplain vegetation. Interpreted as aggrading minor channel deposits topped by a small bar (planar–tabular set) and vertical accretion fines.
trough cross beds, planar tabular cross beds, and ripple cross lamination are also common (Fig. 15). These may, however, stand less chance of preservation than the larger planar tabular sets. In sections observed in river banks (Fig. 13), the scale of cross-bedding and cross-lamination commonly decreases upward, and simultaneously, more layers of silt and mud appear.

**LOCAL MODEL FOR THE S. SASKATCHEWAN RIVER**

The summary, or local model of sedimentation proposed here is a synthesis of geomorphological data with that of bedforms, stratification, and stratification sequence. It is presented both in terms of a block diagram (Fig. 14) and three characteristic stratification sequences (Fig. 15). The general applicability will only be understood after detailed comparison with other modern and ancient braided systems (Walker, 1976a, b; Miall, 1977).

The block diagram is a pictorial synthesis of the detailed descriptions given in this paper, and should need little further comment. It also serves to put in context the three stratification sequences of Fig. 15. The first sequence (Fig. 15) shows maximum influence of sand flat development (A in Fig. 14). Trough cross-bedded channel deposits are overlain by a 1 m thick planar tabular set (cross-channel bar) with a divergent palaeoflow direction. In the block diagram (Fig. 14), fines are shown in black at the downstream end of this planar tabular set—it is suggested that they were deposited in a protected backwater formed between the cross-channel bar front and the two horns. Above the large planar tabular set, the sand flat sequence is dominated by smaller planar tabular sets, cut by minor channels and interrupted by reactivation surfaces. Minor parallel lamination and trough cross-bedding occur, but the top of the sequence is dominated by small planar tabular cross-beds and ripple cross-lamination. If a thin floodplain sequence is preserved, it will consist mostly of silts and clays, with some cross-laminated fine sand, and some well sorted structureless sand blown onto the floodplain by wind.

The third sequence (Fig. 15) is dominated by channel aggradation (C in Fig. 14). The lower part consists of large-scale trough cross-bedding, which may be interrupted by a large planar tabular set, the record of a cross-channel bar that did not develop into a sand flat. Further transport of sand down the channel in the form of dunes would give rise to smaller scale trough cross bedding. The final result of aggradation in such a channel, without sand flat development, would probably be smaller scale bedforms (sand waves and ripples), and possibly deposition of silts and clays if the channel were finally cut off and turned into a slough. The vertical aggradation sediments, if present, would probably resemble those of the sand flat sequence (Fig. 15).

The second, mixed influence, sequence in Fig. 15 is a possible intermediate type, with deposition both in channels and on sand flats (B in Fig. 14). A minor channel with trough cross-bedding is shown scouring into sand flat deposits consisting of a cross-channel bar followed by one planar tabular set. These shallow minor channels do not cut entirely through the sand flat deposits (Fig. 14). The minor channel deposits consist both of trough cross beds and planar tabular sets. The upper part of the mixed influence sequence is shown resembling the sand flat sequence, to suggest re-establishment of the sand flat.

The braided aspect of the South Saskatchewan River is due to the sand flats
Fig. 14. Block diagram summarizing the major morphological elements and their associated bedforms and stratification. The hypothetical reach is outlined by a rectangle in the inset, lower right. Stippled areas are emergent. Single shafted arrows indicate directions of bedform movement, and double-shafted arrows indicate flow directions. A textural stratigraphic sequence dominated by sand flat development (Fig. 15) also has mixed sand flat and channel influence, and C is dominated by channel aggradation. Numbers are explained on the diagram.
Fig. 15. Summary stratigraphic sequences characterizing areas dominated by sand flat development, areas of mixed sand flat and channel influence, and areas of channel aggradation. Arrows indicate in a general way the degree of expected paleoflow variability. Sequences discussed in detail in text.

separating the channels We emphasize that the 'braided' aspect of the sequences shown in Fig. 15 is contained mostly in the sand flat sequence, with the large set of planar tabular cross bedding representing the cross-channel bar. An ancient example is the Battery Point Formation in Quebec (Cant & Walker, 1976; Cant, 1978). The channel aggradation sequence alone (and without record of a cross-channel bar) would probably be very difficult to distinguish from a lateral accretion point bar sequence in a meandering river.

There is additional cause for confusion with meandering sequences, especially now that Jackson (1976) has emphasized the occurrence of planar-tabular sets within point bar sequences. These are deposited by scroll bars, are unidirectional within any one point bar sequence, and occur essentially at the top of the sequence (Jackson, 1976, fig. 13). The large planar tabular set low in our proposed sequences (Fig. 15) is quite different from anything described from meandering sequences, and the variability in direction of the smaller planar tabular sets higher up distinguishes them from Jackson’s scroll bars. More detailed comparisons will be published elsewhere (Cant, 1978).

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