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Sandy Fluvial Systems

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INTRODUCTION

Sandy rivers can be subdivided into four types, straight, meandering, braided and anastomosed. Natural straight rivers are very uncommon, and there is probably a spectrum of types from meandering to braided. The anastomosed type has only recently been emphasized, and a model would probably be premature. We will therefore concentrate on the *meandering* and *braided* end members of the spectrum mentioned above. Comparison of new situations with our meandering and braided *norms* should help to establish the range of variation between the end members; it will also help to define better the end members themselves.

HISTORY OF SANDY FLUVIAL STUDIES

A full historical review has been given by Miall (1978a) – our purpose here is to introduce the reader to the development of ideas during the last 40 years. Before doing so, it is important to note that Barrell (1913, p. 458) had identified fining-upward sequences in the Devonian Catskill Formation of New York State, as had Dixon (1921, p. 32) in the South Wales coalfield. Dixon commented that the sequence: flaggy sandstone grading up into red marl is "repeated interminably and in all parts of the series".

The post-war period of about 1944-1960 was devoted mostly to the study of modern rivers, rather than the sediments therein. Classic work is that of Fisk (1944) on the Mississippi, and of the geomorphologists on various U.S. rivers (notably Leopold, Schumm and Wolman; references in Miall, 1978a).

In about 1960, two separate lines of study began to develop, namely recent sediments in rivers, and ancient fluvial sediments.

Recent sediments were studied by the Shell Oil Company in legendary but mostly unpublished work on Brazos River point bars in Texas (see Bernard *et al.*, 1970), where the classic fining-upward sequence was documented, along with vertical changes in sedimentary structures (giant ripple bedding, overlain by horizontal bedding, overlain by small ripple bedding).

Excavations in the Mississippi Old River Locksite were described by Frazier and Osanik (1961). In the early 1960s, the geometry of various sedimentary structures was still being determined, and this is the emphasis of Frazier and Osanik's work, as well as that of Harms *et al.* (1963), in the Red River of Louisiana. The relationship of fluvial bed forms, stratification and flow phenomena were further emphasized by Harms and Fahnestock (1965) from the Rio Grande near El Paso, Texas. The most significant addition to this work was probably that of Jackson (1976), who related in detail flow phenomena, bed forms and stratification sequences in meanders of the Wabash River.

Studies of *ancient meandering sandstones* blossomed along with the work on recent sediments. Fining-upward sequences were described in detail by Bersier (1968), and in classic work by Allen (1964) which has continued to this day (e.g., Allen, 1983). Low sinuosity streams were discussed by Moody-Stewart (1966) from Spitsbergen, but interpretations of *ancient braided sandstones* have been relatively few (Smith, 1970; Campbell, 1976; Cant and Walker, 1976; Allen, 1983). This may be due to the fact that relatively few *modern braided sandy rivers* have been described sedimentologically; classic studies include the Brahmaputra (Coleman, 1969), Platte (Smith, 1970; Blodgett and Stanley, 1980), Tana (north Norway, Collinson, 1970), and South Saskatchewan (Cant and Walker, 1978).

These studies constitute the core of the data base for the models we present below. For the meandering model, there seems to be much more data from ancient rocks than well-studied modern rivers. The emphasis on Devonian Old Red Sandstone/Catskill examples may bias the model toward smaller meandering streams. The data base for braided systems is much smaller – the four or five rivers mentioned above, together with a very small (but growing) number of interpretations of ancient braided sandstones.

MEANDERING SYSTEMS

The main elements of a modern meandering system (exemplified by the Mississippi or Brazos rivers) are shown in Figure 1. Sandy deposition is normally restricted to the main channel, or to partially or completely abandoned meander loops; deposition of fines (silt and clay) occurs on levees and in flood basins.

Basis For The Model

The model has been developed from both modern and ancient sediments. The most important papers on modern meandering streams used in developing the model are those of Sundborg (1956; River Klaralven), Harms *et al.* (1963; Red River), McGowen and Garner (1970; Colorado (Texas) and Amite rivers) and Jackson (1976; Wabash River), five in all.

Investigations of larger-scale processes such as meander loop migration, rates and patterns of channel switching and aggradation remain sparse. Many descriptions of ancient meandering stream deposits have also been integrated into the model, to the extent that the model is one of the most broadly based facies models in terms of numbers of modern and ancient examples used. However, much remains to be done in terms of documenting and understanding variations of the model.

The Channel And Point Bar

Meandering of the channel is maintained by erosion on the outer banks of meander loops, and deposition on the inner parts of the loops. The main depositional environment is the point bar, which builds laterally and downstream across the flood plain.

The channel floor commonly has a coarse "lag" deposit of material that the river can only move at peak flood time.

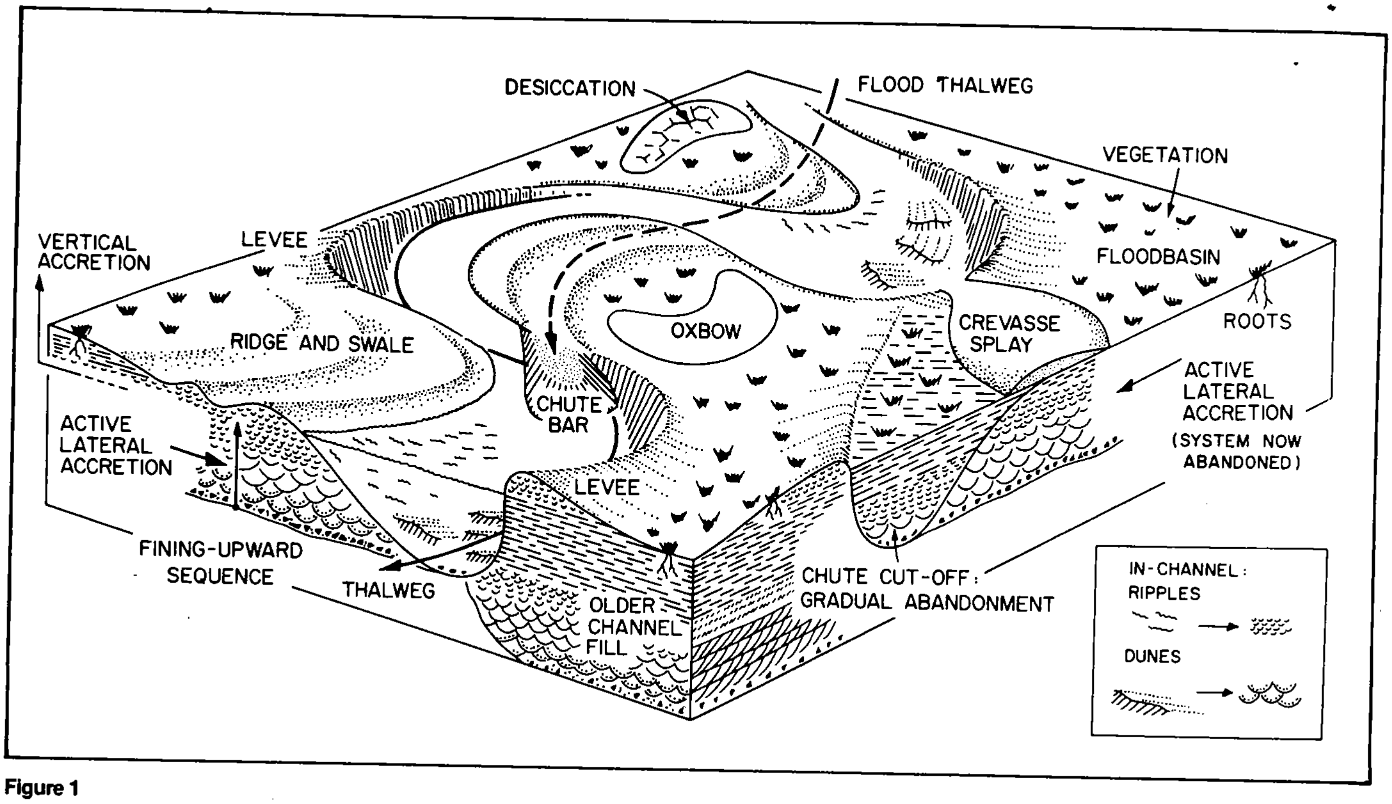


Figure 1
Block diagram showing morphological elements of a meandering river system. Erosion on the outside bend of a meander loop leads to lateral accretion on the opposite point bar. The dunes and ripples in the channel give rise to trough cross bedding and ripple cross lamination respectively (inset, lower right), which are preserved in a fining-upward sequence. See text for details.

This material includes the gravelly component of the clastic load, together with water-logged plant material and partly consolidated blocks of mud eroded locally from the channel wall. Above the lag, sand is transported through the system as bedload. During average discharge, the typical bedform on the channel floor consists of sinuous-crested dunes (Fig. 1) ranging in height from about 30 cm to one metre. Preservation of these dunes results in trough cross-stratification. In shallower parts of the flow, higher on the point bar, the bedform is commonly ripples (preserved as trough cross lamination, Fig. 1). As a broad generalization, we may propose that the preserved deposits of the active channel will pass from trough cross-bedded coarser sands to small scale, trough cross-laminated finer sands upward (Fig. 1).

The development of a plane bed (without ripples or dunes) is favoured by higher velocities, shallow depths and finer grain sizes. Deposition on the plane bed results in horizontal lamination. The particular combinations of depth and velocity required to produce a plane bed can occur at various river stages, and hence parallel lamination can be formed both low and high on the point bar. It can therefore be preserved interbedded with trough cross-bedding, or small scale trough cross-lamination (Figs. 2 and 3).

The sequence shown in Figure 2 is typical of Devonian Old Red Sandstone/Catskill deposits, but does not necessarily characterize deeper or flashier rivers. Very little attention has been given to the response of the sedimentary structure sequence to stage changes in meandering rivers. Also, many modern point bars appear to be terraced (Fig. 4), perhaps due to incision and erosion, or perhaps due to different levels of deposition at various flood stages. The relationship of structure sequence to terracing has not been investigated.

The fining-upward grain size change is a response to spiralling flow through the meander loop. Slightly higher water elevations on the cut-bank side drive a flow down toward the bed and up onto the point bar – the combination of this cross-channel flow with downchannel flow results in spiral flow. Gradually decelerating flow components up the point bar result in the transport of finer and finer sediment, and the general transition from sinous crested dunes (in channel) to small current ripples (near top of point bar).

Erosion of the cut bank and deposition on the point bar result in a gradual lateral and downcurrent shift in position of the point bar. The fining-upward sequence of grain sizes, and accompanying vertical sequence of sedimentary structures, is therefore preserved by LATERAL ACCRETION of the point part (Fig. 1). If the lateral accretion is episodic, or if there are periods of erosion during overall accretion, former positions of the point bar surface can be preserved within the sedimentary sequence. These surfaces are characteristically sigmoid (flat on top of the point bar, steepening down the point bar, and flattening again into the channel floor), with dips of a few degrees up to a maximum of around 15°. They are termed *lateral accretion surfaces* or *epsilon* cross beds (Fig. 5).

Channel Abandonment

Meander loops can be abandoned gradually (chute cut-off) or suddenly (neck cut-off) (Allen, 1965, p. 118-9, 156). During chute cut-off, the river gradually re-occupies an old swale, and

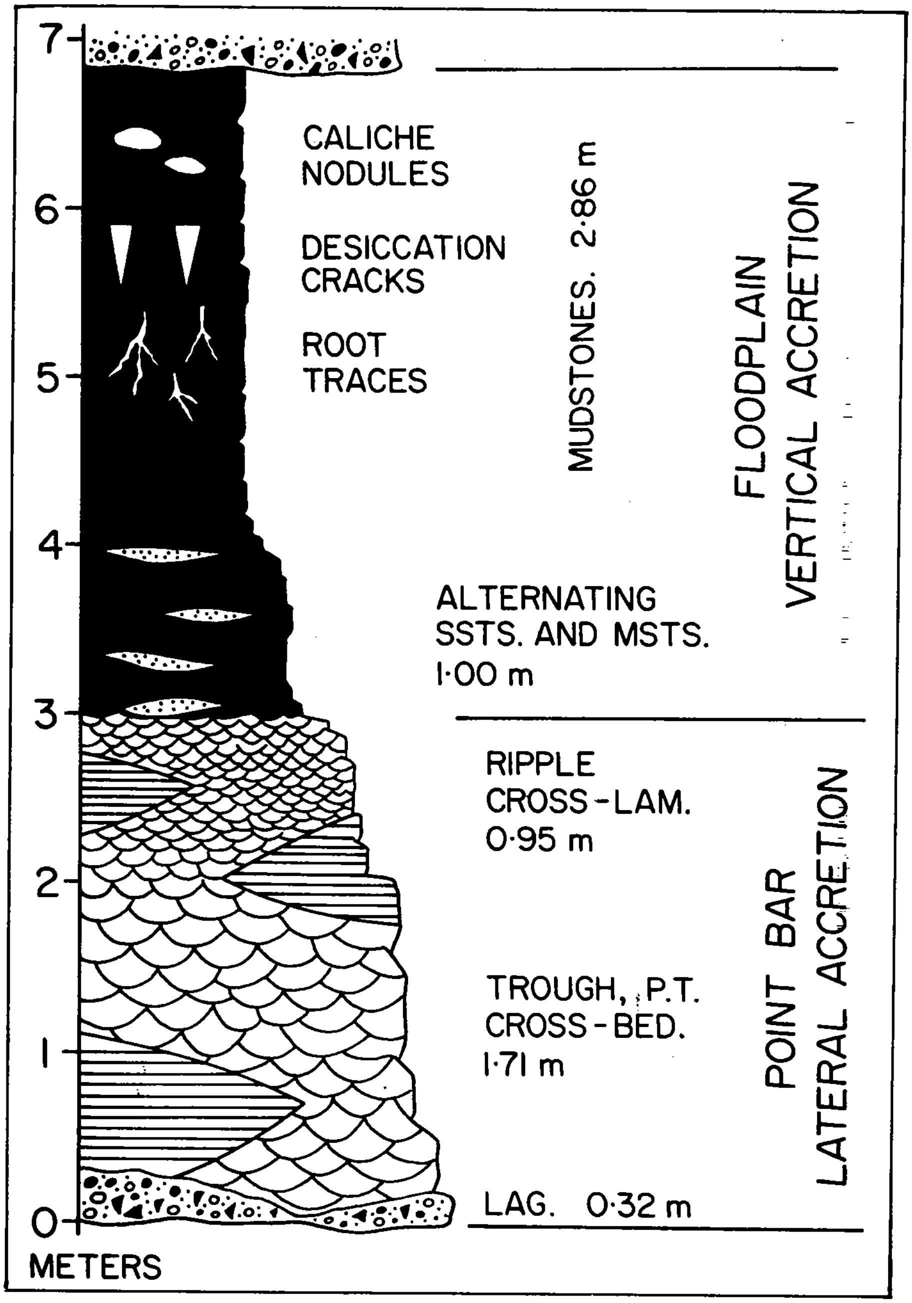


Figure 2
Model for lateral and vertical accretion deposits of meandering rivers. Data on facies sequence and fining upwards cycles summarized here are from the Devonian Old Red Sandstone of Britain and the Catskill rocks of the eastern U.S.A. (Allen, 1970). The average lateral accretion deposit is 2.98 m thick, and the vertical accretion deposit averages 3.86 m. Thus the average sequence is 6.84 m thick. Compare with braided stream sequences in Figures 17 and 19. Note that parallel lamination can replace trough cross bedding or ripple cross lamination, or both. The average thickness of parallel lamination is 1.30 m.

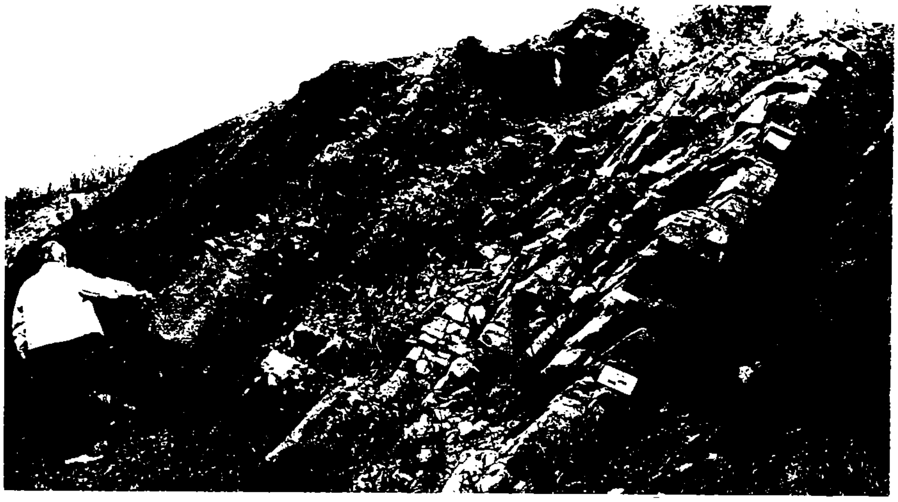


Figure 3
Fining-upward sequence, Cretaceous Belly River Formation, on Trans-Canada Highway between Calgary and Morley Road. Note sharp base to sand body, and cross bedding (by notebook) in lower part. Upper part of sand body (by geologist) is ripple cross laminated and overlain by fines.

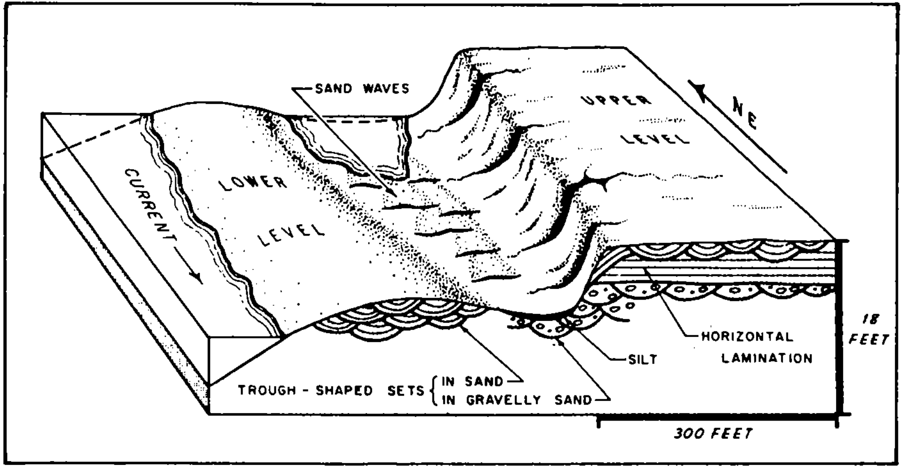


Figure 4
Block diagram showing upstream part of Beene Point Bar, Red River, Louisiana, from Harms et al. (1963). Note terracing (2 levels) on the point bar, and interbedding of various sedimentary structures.

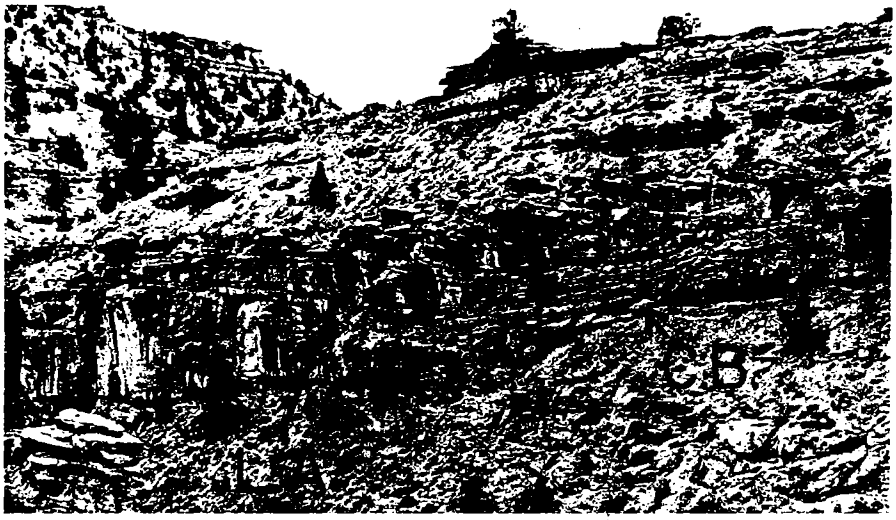


Figure 5
Lateral accretion surfaces (epsilon cross strata), Gate Canyon (near Nine Mile Canyon, Utah). In these fluvial Eocene sandstones and shales, note erosive base of sand body. Superbly developed lateral accretion surfaces (L.A.), with overall aggradation during lateral accretion, and cut bank (C.B.) on opposite side. Main sand body about 5 m thick.

simultaneously flow gradually decreases in the main channel. Gradual abandonment thus results in gradual flow decrease, and this could be reflected in the sediments by the development of a thick sequence of low-flow sedimentary structures – essentially ripple cross-lamination (Fig. 6). After complete abandonment, forming an ox-bow lake, sedimentation would be restricted to fines (silt, mud) introduced into the ox-bow during overbank flooding from the main stream (Fig. 1).

Neck cut-off involves the breaching of a neck between two meanders, and the sudden cut-off of an entire meander loop. Both the entrance to and exit from the loop tend to be rapidly plugged with sand. Flow diminishes to zero rather quickly and the resulting sequence of deposits is dominated by later, flood-introduced silts and muds (Fig. 6).

Vertical Accretion Deposits

Outside the main channel, deposition in the flood basins, ox-bows and levees takes place by addition of sediment during flood stage when the river overtops its banks (Fig. 1). In contrast to the lateral accretion within the main channel, overbank deposition causes upbuilding of the flood plain, hence the term VERTICAL ACCRETION. Near to the main channel, where the flood waters sweep along as a stream, the vertical accretion deposits tend to be silty, and are commonly cross-laminated. In some cases, it appears that the levee is breached catastrophically, and the resulting splay bed has a sharp base and begins with parallel lamination. This may pass upward into ripple cross lamination, producing a bed which is descriptively and hydrodynamically akin to a turbidite. It can be distinguished from a deep marine turbidite (see "Turbidites and Associated Coarse Clastic Deposits", this volume) by its context, and the possible root traces in the top of the splay bed.

Farther from the river, flood waters may stagnate and only mud is deposited. After retreat of the flood, the mud and silt commonly dry out, and desiccation cracks are formed. The flood basins and levees of most river systems (post-Silurian) tend to be abundantly vegetated, and hence the deposits commonly contain root traces. In some climatic regimes, the vegetation may grow sufficiently abundantly to form coal seams. In semi-arid environments, the fluctuating water table and drying at the surface favour the formation of caliche-like nodules within the vertical accretion deposits.

The only other deposits that may rarely be preserved as part of the vertical accretion sequence are windblown, and may be either loess, or coarser sandy deposits blown in as large dunes (see "Eolian Facies", this volume).

Meandering River Facies Sequence

The distillation of observations from a large number of modern meandering streams, and from many ancient formations interpreted as meandering-fluvial, allows a general facies sequence to be formulated. One version of this sequence is shown in Figure 2; it was distilled statistically by Allen (1970) and is redrawn to scale here. In its simplest form, the sequence is FINING-UPWARD and consists of in-channel deposits (lateral accretion), followed by overbank fines (vertical accretion) (Figs. 7 and 8).

In this particular sequence, the facies relationships were determined statistically for a large number of Devonian outcrops in Britain and North America, but application of the model has demonstrated that it can be used appropriately in many other areas. The lag

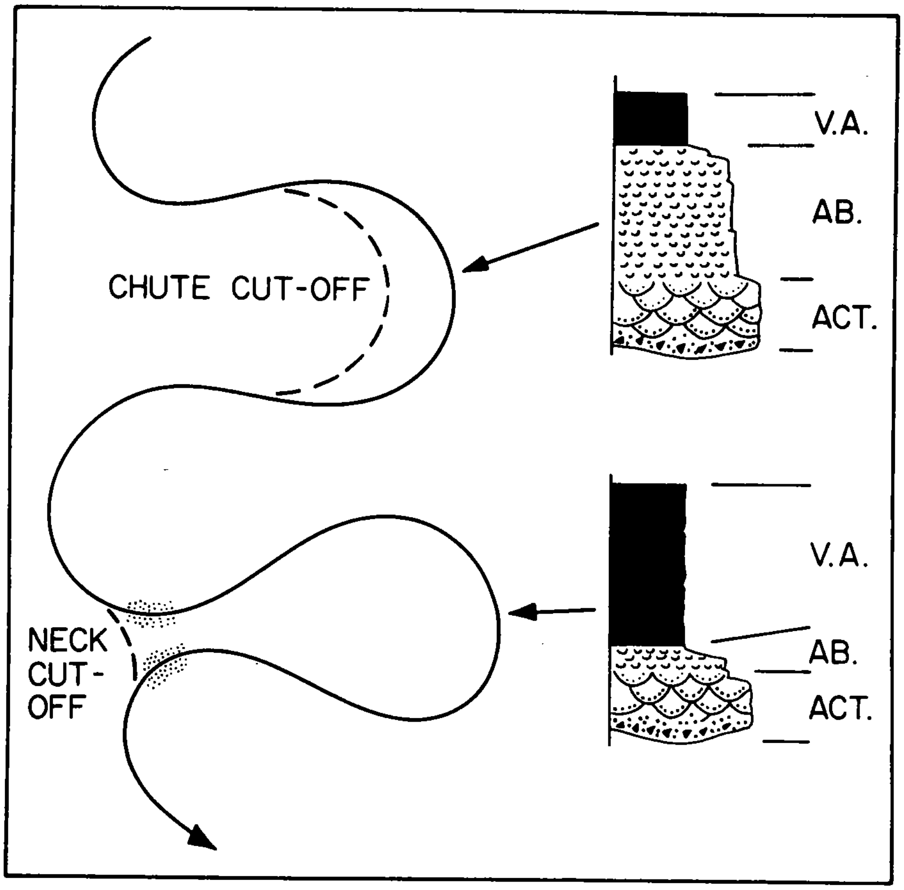


Figure 6
Meander loops can be abandoned by chute or neck cut-off. Old channel shown solid, new channels dashed. Chute cut-off involves reoccupation of an old swale and gradual abandonment of the main channel. The stratigraphic sequence will consist of some trough cross-bedded deposits of the active river (ACT) and a thick sequence of ripple cross-laminated fine sands representing gradual abandonment (AB). After cut-off, the sequence is completed by vertical-accretion (V.A.) deposits. By contrast, after neck cut-off, the meander loop is suddenly abandoned and sealed off by deposition of sand plugs (stipple). After the active deposits, the ripple cross-laminated fine sands representing low flow during abandonment (AB) are very thin, and the bulk of the sequence consists of vertical-accretion (V.A.) deposits washed into the abandoned loop at flood time. Compare with the active lateral-accretion sequence (Fig. 2).

Figure 7
A complete fining-upward sequence from the Pennsylvanian Maringouin Formation, Nova Scotia. Note sharp base, and interbedding of sandstones and shales toward top of sand body. Vertical accretion fines separate the interbedded sandstones and shales from the next sand body (top left). Directly above geologist's head is a small mud-filled channel that cuts out the interbedded sandstones and shales - it may represent an abandoned swale on a point bar.

Figure 8

Photomosaic of a multistory sand body with well-developed lateral accretion surfaces in lower part (LA). Sand body is about 15.5 m thick; Lower Cretaceous Gladstone Formation at Bighorn River, Albĕrta. The upper part of the sand body is inaccessible, but possibly contains smaller lateral accretion sets, or possibly huge wide shallow troughs dipping toward the reader in the left-hand half of the uppermost sand body.

deposits are overlain by trough cross-bedding, which is in turn overlain by small scale trough cross-lamination. Horizontal lamination can occur at several places within this sequence (Fig. 2), depending on the river stage at the time when the depth/velocity/grain size criteria for plane bed were met.

After the channel migrated away laterally, the facies sequence continued with vertical accretion deposits introduced at flood stage. The diagram (Fig. 2) shows root traces, desiccation cracks and caliche-like concretions. Using the data presented by Allen (1970, Table 9), it can be seen that the vertical and lateral accretion deposits in the meandering model are on average roughly equal in thickness.

Allen's model serves excellently as a norm with which to compare other fining-upward sequences. Comparison of sequences such as those in Figure 6 with Allen's norm immediately shows that the trough cross-bedding is very reduced in thickness, that the chute cutoff sequence contains an abnormal thickness of ripple trough cross-lamination, and that both contain unusual thicknesses of vertical accretion deposits. The comparison with Allen's model suggests the interpretations shown in Figure 6; without the model, we would not be so conscious that the sequences in Figure 6 differed significantly from the sequence developed by lateral accretion in an active channel.

The rocks in Figure 8 also emphasize the role of Allen's model as a norm. In Figure 8, both the sandstones and mudstones are much thicker than suggested by the norm. There are possibly two superimposed sets of lateral accretion deposits in the sandstone, suggesting two superimposed channel sands rather than one extremely thick sand body. The apparently unusual thickness of vertical accretion fines will be discussed again below.

Comparison of the models with some sequences developed for meandering rivers with slightly coarser loads also reveals some differences. Where coarse bedload is funnelled by flood waters through a swale on the top of a point bar, a much straighter thalweg is formed. The coarse material is dumped at the downstream end of the swale forming a chute bar adjacent to the point bar (Fig. 2; McGowen and Garner, 1970). In other rivers, coarser sediment and less mud deposition leads to a sequence without a really well developed fining-upward trend (Jackson, 1976). These variations from the standard point bar model must be recognized and allowed for in the study of ancient sediments.

Sand Body Geometry And Flood-Plain Aggradation

One of the essential components of a meandering model is the fact that meander loops are cut off, abandoned, and ultimately filled with fines - silt and clay. Through time, these clay plugs, along with thick back-swamp clays, may become abundant because the plugs are relatively hard to erode. Once confined, the entire meander belt may become raised above the general level of the flood plain by vertical accretion (Fig. 9A). This situation can persist until one catastrophic levee break results in the sudden switch of the entire river to a lower part of the floodplain ("avulsion", Fig. 9A). Thus the overall sand body geometry of a highly sinuous meandering stream will be essentially elongate ("shoestring"), bounded below and on both sides by flood-basin fines. The shoestring will also stand a good chance of being covered by overbank fines from the active river in its new position. Thus the *high sinuosity meandering model* predicts that, given continuing supply and basin subsidence, a series of point bar sand sheets interbedded with shales should be developed within the overall shoestring geometry. The internal structure of the point bar sands themselves should conform roughly to the pattern shown in Figure 1. A single-sequence sand body should be about as thick as the river was deep; however, if clay plugs restrain the river to the meander belt, multistory sand bodies should be common (Figs. 8 and 9A). Sequences of overbank fines thicker than those predicted by Allen's model could form if the river is confined in this way - compare the mudstones in Figure 8 with those in Figure 2. Conversely, using this model as a predictor, we suggest that unusually thick sequences of vertical accretion fines (10 m +) might predict (along strike) stacked sand bodies in a meader belt confined by clay plugs. The vertical scale in Figure 9A is considerably exaggerated, and individual shoestrings will probably be many times wider than they are thick.

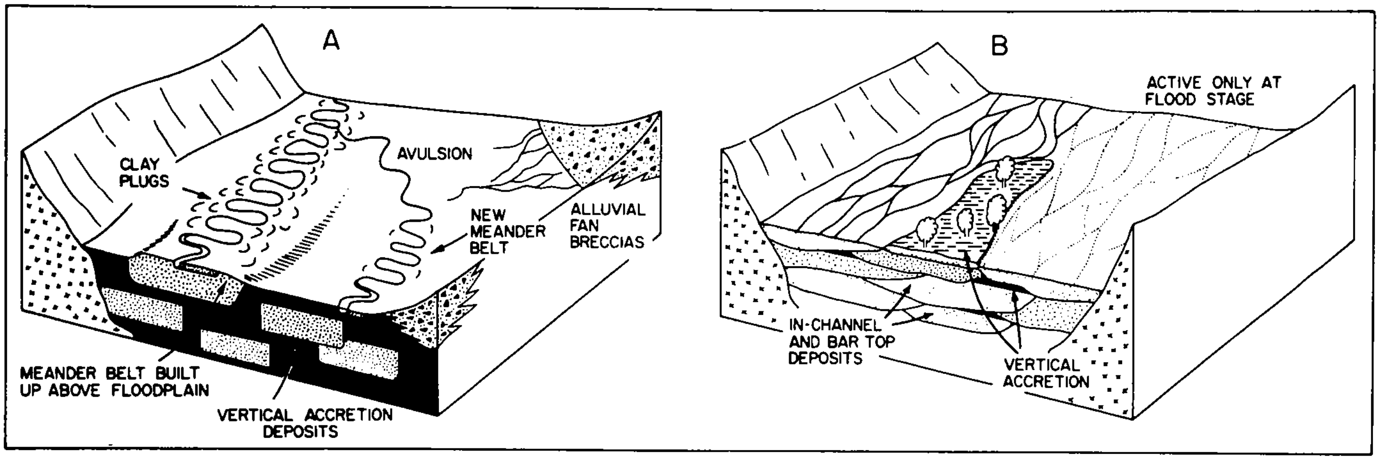


Figure 9
A) block diagram of flood plain aggradation with very sinuous rivers. Shoestring sands are preserved, and are surrounded by vertical accretion siltstones and mudstones. If the river is confined by clay plugs, very thick vertical accretion deposits can form without erosion. B) block diagram of sandy braided system with low sinuosity channels. Vertical accretion can occur during flood stage, but deposits are rarely preserved. Diagrams modified from Allen (1965).

Meandering Rivers In The Subsurface

There are many examples: we highlight two to illustrate how well-log data (see "Subsurface Facies Analysis", this volume) can be used in fluvial reconstructions. In the Lower Cretaceous sandstones in the Powder River basin, Wyoming, Berg (1968) has shown well-log correlations which can be interpreted in terms of: 1) porous point bar sands; 2) sands, silts and shales of swale-fill origin; and 3) shale and silt representing the fill of the abandoned channel (Fig. 10). Note the thickness of the point bar sand - up to about 75 feet, or 23 m. In the isopach map (Fig. 11), the shapes of the meander loop and swales are apparent. The isopach map does not suggest superimposed separate sand bodies - it appears to be one system 23 m deep which accreted laterally toward the NE. The size of this meander loop (radius of curvature about 2130 m) is comparable with loops in the modern Mississippi and Missouri rivers, which helps to explain the unusually great depth of this Cretaceous river.

In a second example, Hopkins *et al.* (1982) have presented subsurface data for Lower Cretaceous Mannville Group sands in southern Alberta (Figs. 12 and 13). Here, the Mannville channels are incised into older units (Ostracod Limestone and Bantry Shale, Fig. 13), and at least the lower ones were probably not freely meandering. Part of the line BB' (Fig. 12) is shown in Figure 13, and can be interpreted in terms of a laterally accreted sandstone about 20 m

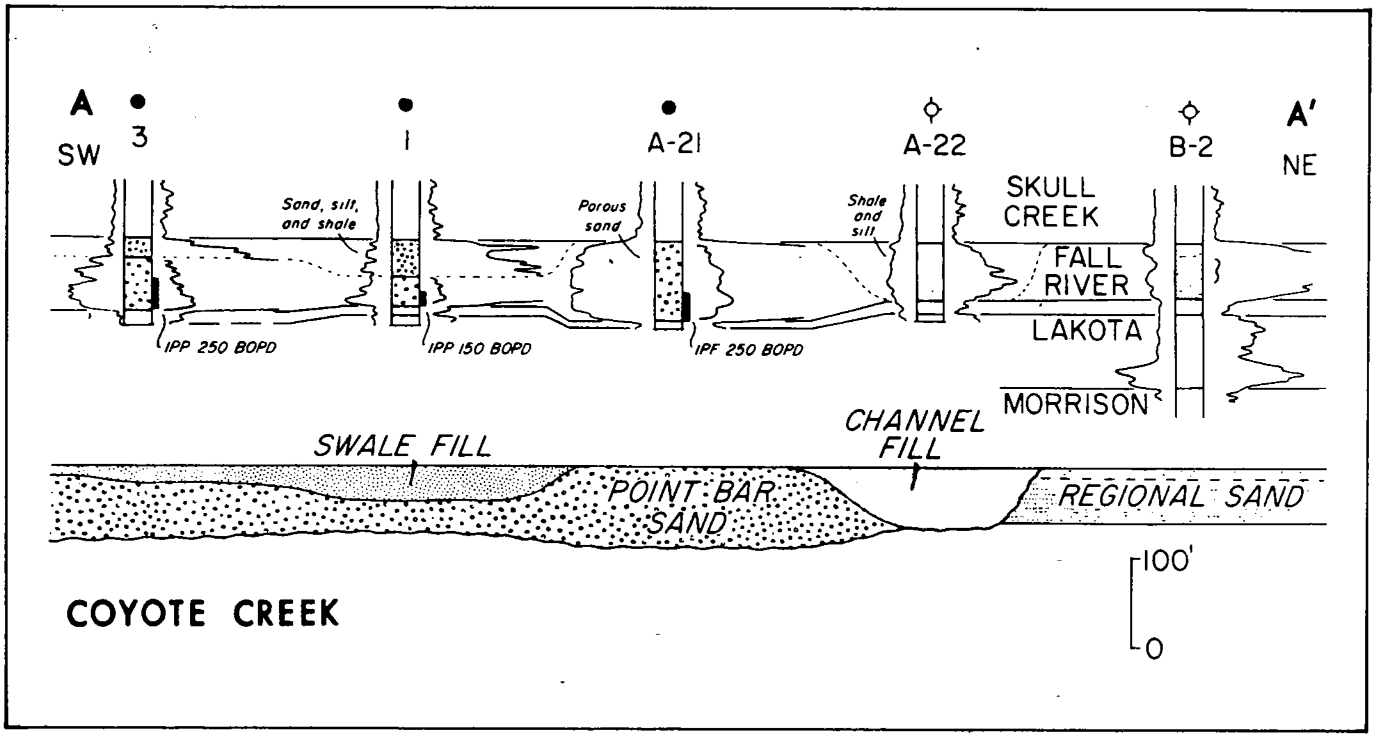
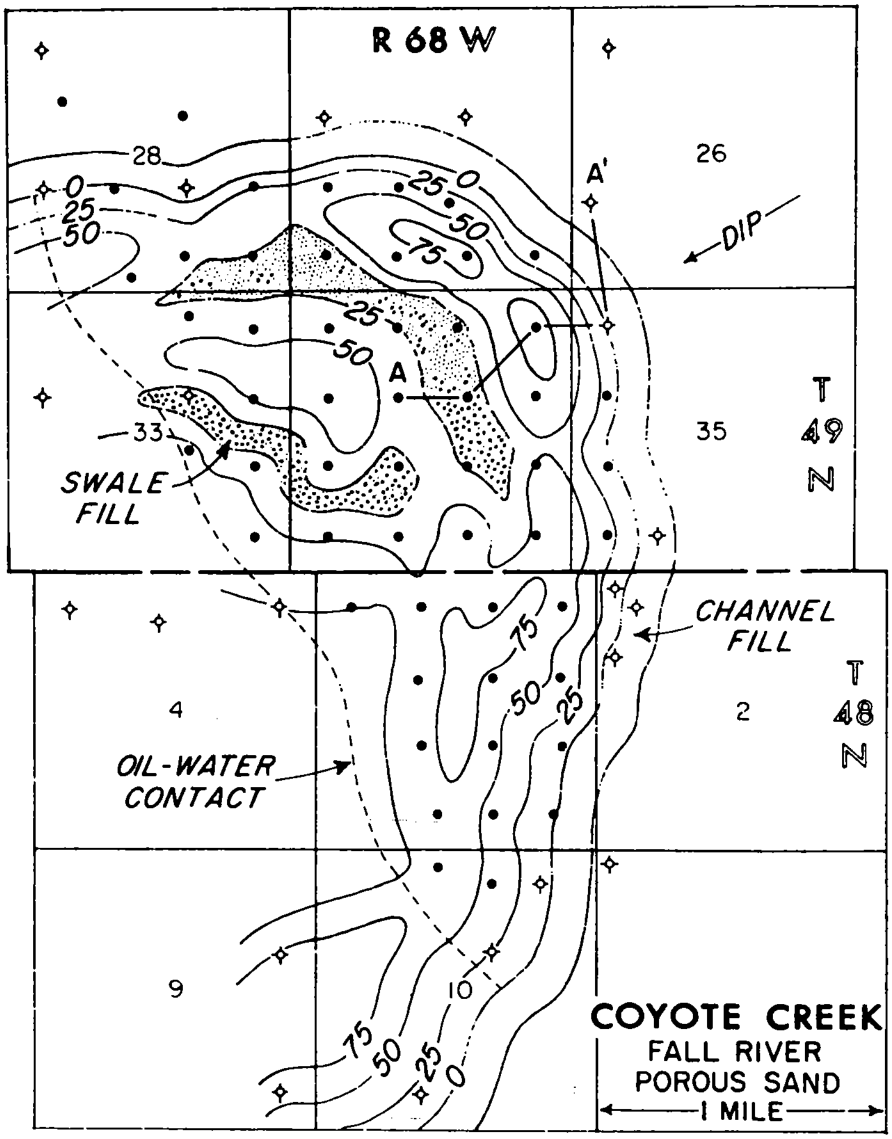


Figure 10
Correlation of well logs (SP, resistivity) across Coyote Creek field (location in Fig. 11), with interpretation in terms of meander belt facies below. Note thickness of sand body - about 50 to 75' (15 to 23 m); channel width is about 1500 to 2000' (460 to 610 m). From Berg (1968).



◀ Figure 11
Isopach map of Coyote Creek field, northeastern Wyoming. Note location of cross-section AA' (Fig. 10). Swale fills show thinner sands, and the abandoned meander loop itself has no sand. This can be seen both in the sand isopach (values down to zero) and the location of dry holes (open circles) as opposed to oil wells (black circles). From this isopach map, Berg (1968) made the following estimates: channel width 1500 to 2000' (460 to 610 m), meander radius 7000' (2130 m) and meander wavelength 40000' (about 12,200 m). Note that the regional dip is southwestward, and hence the shaly fill of the abandoned meander loop is the updip stratigraphic trap. From Berg (1968).

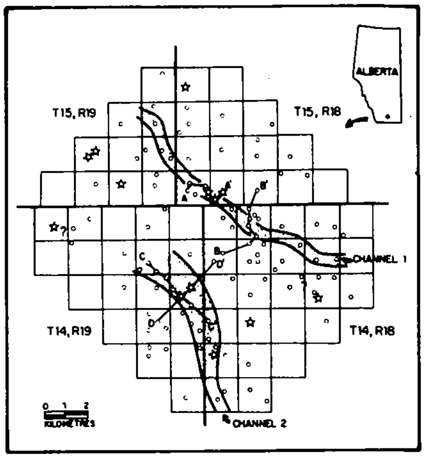


Figure 12
Location map of Little Bow area, southern Alberta. Location of two channels shown. Figure 13 shows cross section BB', omitting the wells at each end of the line. Glauconitic Member of the Mannville (Albian), from Hopkins et al., *1982.*

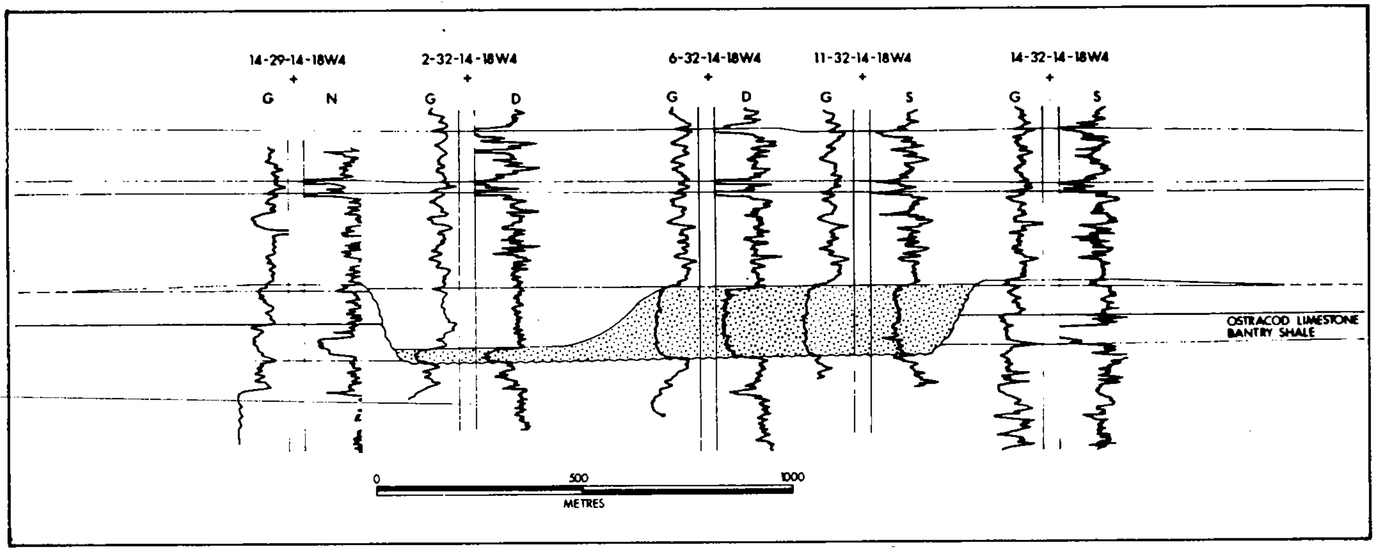


Figure 13
Part of cross-section BB' (see Fig. 12) from the Glauconitic member of the Mannville (Albian), from Hopkins et al. *(1982). From the correlations shown, note the laterally accreting sand body from well 11-32 to 6-32, and then abandonment of the system with subsequent mud filling of the empty channel (well 2-32). The laterally accreted sand is about 20 m thick, the empty channel about 500 m wide, subsequently filled with about 16 to 17 m of fines.*

thick (wells 6-32 and 11-32), with a channel some 500 m wide that filled with 16 to 17 m of mud after cut-off of this meander system (? by avulsion). The overall, incised channel width (Fig. 12) is about 1 km, suggesting that the 500 m quoted above (Fig. 13) represents the width of a meandering channel within the overall, straighter incised channel. This channel width (500 m) is comparable to the narrower parts of the present Missouri River.

In both examples, the simple models of Figures 1 and 2 must be use with caution in prediction, because the models are based upon much smaller rivers than those in Figures 11, 12 and 13, and because of the problem of river incision into older rocks.

Point Bar Reconstructions

Since earlier versions of this paper, several excellent reconstructions of ancient point bars have been made, particularly those of Nami (1976), Nami and Leeder (1978), Nijman and Puigdefabregas (1978) and Edwards *et al.* (1983). In some of these studies, the sand bodies are a little thicker than those in the sequence of Figure 2 (Nami and Leeder quote 3 to 9 m, and Nijman and Puigdefabregas quote a maximum of 11 m), although the 2 to 3 m thick epsilon cross beds quoted by Edwards *et al.* (1983) are very comparable with Figure 2. The importance of these studies is that three dimensional reconstructions of channel, point bar and swales can be made from excellent outcrops, allowing a direct link between modern point bars and preservability of facies in the geological record.

SANDY BRAIDED SYSTEMS

The fundamental processes that control whether a river has a braided or meandering pattern are not completely understood but we do know that braiding is favoured by rapid discharge fluctuations of a greater absolute magnitude than in meandering rivers. Braided rivers also tend to have higher slopes, a heavy load of coarse sediment, and more easily erodible banks. In combination these features would suggest that braiding is more characteristic of the upstream reaches of a river, with meandering becoming more common downstream as the slope and coarseness of load decreases. Braiding would also be more common in semi-arid or arid areas.

Basis For The Braided Model

In contrast to meandering rivers, sandy braided systems have received relatively little study. The best known rivers include the Durance and Ardeche (Doeglas, 1962), Brahmaputra (Coleman, 1969), Platte (Smith, 1970; Blodgett and Stanley, 1980), Tana (Collinson, 1970) and South Saskatchewan (Cant and Walker, 1978).

Few studies of braided rivers have been detailed and comprehensive enough to contribute to the models. The scale of the rivers studied varies enormously, from the Platte (1 to 2 m deep, hundreds of metres wide) to the Brahmaputra (up to 25 m deep, several kilometres wide). Relatively few ancient studies have been integrated as yet into braided stream models. The best documented studies include those of Moody-Stewart (1966, Devonian of Spitsbergen), Kelling (1968, Coal Measures, South Wales), Conaghan and

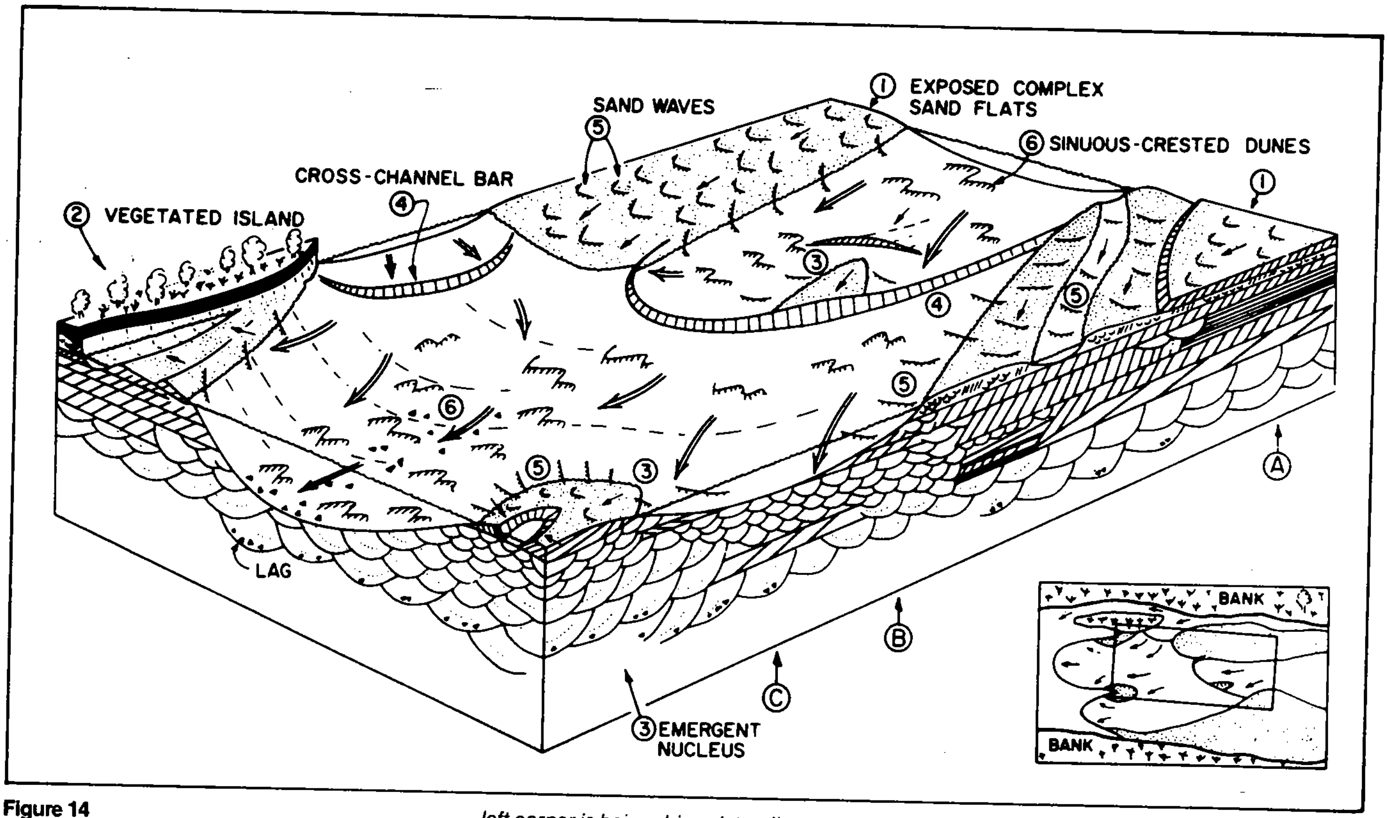


Figure 14
Block diagram showing elements (numbered) of a braided sandy river, based on the South Saskatchewan. Stippled areas exposed, all other areas underwater. Bar in left corner is being driven laterally against a vegetated island, but is separated form the island by a slough in which mud is being deposited. Large sandflats (e.g., right-hand corner) may develop by growth from an emergent nucleus on a major cross-channel bar (see Figs. 15 and 16). Vertical fining-upward sequences A, B and C are shown in Figure 17 and include in-channel and bar top deposits. See text for details.*

Jones (1975), and Jones and Rust (1983, both on the Hawkesbury Sandstone, Australia), Campbell (1976, Morrison Formation, New Mexico), Cant and Walker (1976, Devonian Battery Point Formation, Quebec), Allen (1983, Devonian Brownstones, Welsh Borderlands) and Haszeldine (1983, Upper Carboniferous, north-eastern England). However, the data presented in these studies are diverse, and modern and ancient studies cannot yet be fully integrated into a coherent model.

Braid Bars And Channels

The morphological elements of these rivers (Fig. 14) are complex, and include (in increasing scale) individual bedforms, small "unit" bars, bar complexes (or sandflats), and mature vegetated islands. The river itself flows over and between these sand accumulations in a constantly branching and rejoining braided pattern. The finer material (silt and clay) tends to be transported through the system without accumulation.

The channels tend to be very variable in depth and width, and do not conform to the simple pattern shown by meandering rivers. The channel floor commonly has a lag deposit, and above the lag, sand is transported through the system as bedload. Bedforms in the deeper channels (3 m or deeper) tend to be sinuous crested dunes that give rise to trough cross-bedding. Deposition within channels during waning flood stage can cause channel beds to aggrade, preserving flood stage sedimentary structures. In shallower channels, and on bar tops when they are submerged at flood stage, small dunes and straight-crested to rhomboid sandwaves (Harms *et al.* 1982) are common (Fig. 14, number 5).

Also in the channels are wedge-shaped foreset-bounded transverse or oblique bars. In the South Saskatchewan these can extend across the entire widths of channels, and are termed cross-channel bars (Fig. 15; Cant and Walker, 1978). They form where 1) a smaller channel discharges into a deeper one (as a microdelta), 2) where the flow spreads laterally, or 3) where the flow is forced by channel patterns upstream to flow obliquely across the main river system. This can result in a bar near the bank of the river, generally elongated parallel to the channel trend, but with foresets facing the channel bank (left hand end of Fig. 14). In the Platte and Tana rivers many bars have a more regular linguoid pattern, commonly in an en-echelon arrangement, but this may reflect only a more complete remolding of the bed by high stage floods than in the South Saskatchewan.

Figure 15
Cross channel bar linked to bank in foreground. Nucleus (N) has given rise to two simple horns, and the entire cross channel bar has apparently migrated downstream by a distance equal to the length of the horns. Note smaller nuclei (n) near bank in foreground.

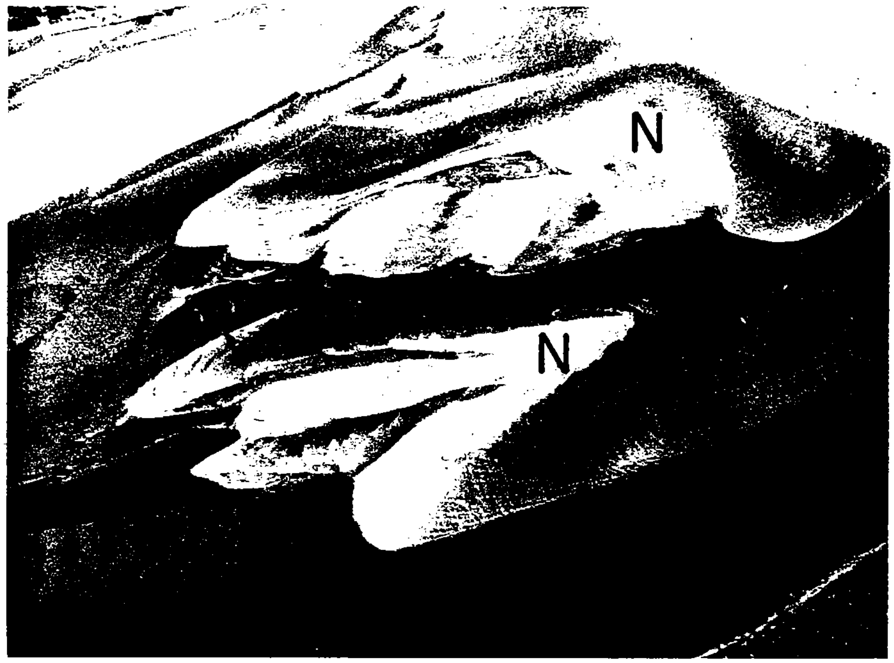


Figure 16
Evolution of a large sand flat by the coalescing of two nuclei (N) with extensive horns. Note that even the low-stage channel (C) does not have erosive margins, and appears to be aggradational. South Saskatchewan River, flow toward bottom left.

Many of the cross-channel bars in the South Saskatchewan have a higher area which is emergent at low stages (Figs. 14 and 15; Cant and Walker, 1978). This high area may act as a "nucleus" for further deposition. The nucleus grows by lengthening downstream as sand is swept around in two "horns" (Fig. 15), and it also grows in the upstream direction as dunes and sand waves are driven up from the channel floor. As the nucleus grows, possibly with other bars coalescing onto it, the original unit bar expands into a large sandflat (Cant and Walker, 1978; Fig. 16). The South Saskatchewan sandflats are complex, and their original shape has been obscured by dissection and redeposition during changing river stage (Fig. 14). They are one to two km long in the South Saskatchewan, three km in the Tana (Collinson, 1970) and up to 10 km in the Brahmaputra (Coleman, 1969). In the South Saskatchewan, they remain constant for at least five to six years, and because of their size, they would seem likely parts of the braided system to be preserved in the stratigraphic record.

From our understanding of the South Saskatchewan (Cant and Walker, 1978), we propose a series of stratification sequences (Fig. 17) that might characterise the deposits of this type of river. The channel sequence (Fig. 17) would consist of a lag, overlain by trough cross stratification formed by migrating sinuous-crested dunes. Sandflat development appears to be initiated by the development and emergence (during falling stage) of a cross channel bar, which would be represented by a thick (0.5 to 2 m) set of planar-tabular cross bedding (Fig. 14, number 4). Nucleus aggradation, and horn growth and modification during a series of floods and falling stages (Fig. 18) would give rise to a complex set of small (tens of cm) planar tabular cross beds. A spectrum of sequences between channel aggradation and sandflat development probably exists, depending on where the sequence developed - in a deep channel, or in the immediate vicinity of a nucleus (compare Figs. 14 and 17).

The sandy tops of all of these sequences are composed of smaller planar and trough cross beds, and rippled sands, making up the feature termed bar top* in Figure 14. The bar top* (with asterisk) implies that deposition and modification are not restricted to the exposed bar tops, but may also take place in shallow dissection channels. The terminology of in-channel and bar top* was first used for ancient rocks (Cant and Walker, 1976; Fig. 19); it is important that the same terms be used for ancient and recent sediments where possible.

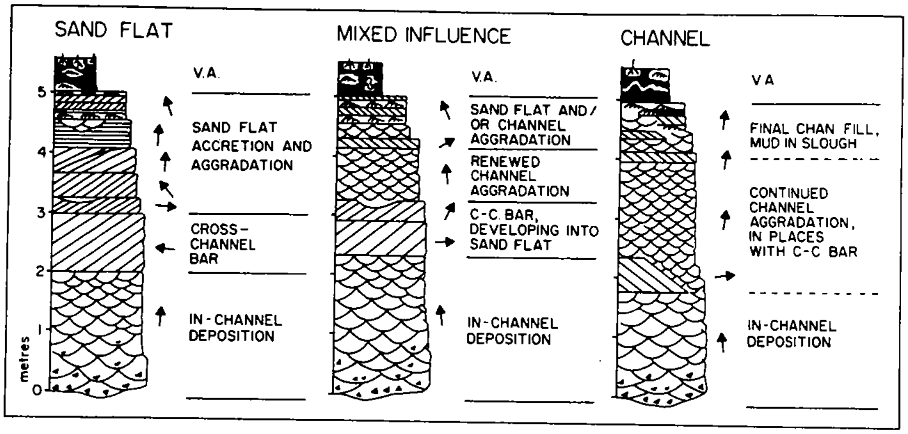


Figure 17
Three proposed sequences of sedimentary structures based on the South Saskatchewan. "Sand flat" corresponds to A (Fig. 14), "channel" to C, and "mixed influence" to B. Arrows indicate generalized paleoflow directions, and sequences are explained in the text.

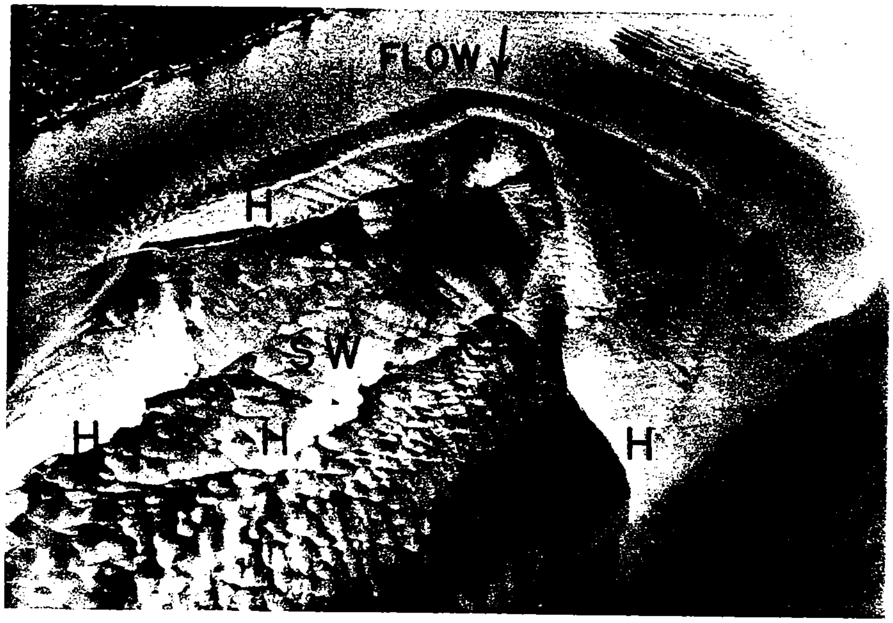


Figure 18
Large sand bar in the South Saskatchewan river; the original position of the nucleus (N) can only be estimated. Several horns (H) have developed from the nucleus, and relict positions of the inward facing sharp, steep crests of the horns can be seen. However, during stages of higher flow, the horns have been modified into a series of straight-crested sand waves (SW); the sand wave crests strike across the horns, and indicate downchannel flow at high stage, not flow expansion during falling stage in the lee of the nucleus (see Figs. 15 and 16).

Vertical Accretion Deposits

In contrast to meandering streams, the vertical accretion deposits of braided streams are less commonly deposited and only rarely preserved. Only during major floods does the river spill from its main channel system onto the surrounding flood plain. In the South Saskatchewan, the braided portion is essentially confined between Pleistocene bluffs. Consequently, the narrow flood plain and the vegetated islands can be relatively easily submerged and receive vertical accretion deposits. In the Platte River, a great deal of sand is swept into the overbank area.

The Brahmaputra spills into its flood basins every year, but the clays settling from the flood waters are deposited slowly, with thickness of two cm or less per annum. However, vegetation is abundant in these flood basins and peat deposits one to four metres in thickness are forming (Coleman, 1969, p. 232-3). These various sub-environments of the braided sandy system are sketched in

Figure 14, but there is certainly more complexity in the deposits than is indicated in the diagram.

Ancient Sandy Braided Fluvial Deposits
We will discuss in some detail the Battery Point Sandstone of Gaspé, Quebec and the Brownstones of Wales as examples of ancient sandy braided fluvial deposits.

The Battery Point section studied (Cant and Walker, 1976) could be subdivided into 8 facies based on sedimentary structures and grain sizes. At least 10 fluvial sequences of the type summarized in Figure 19 could be identified in the measured section. The order of occurrence of facies was "distilled" (Walker, "General Introduction" to this volume) in order to look for a general facies sequence that could act as a basis for interpretation - see also Miall (1973) and Cant and Walker, 1976, p. 111-114). The end result of the Battery Point distillation is the sequence shown here in Figure 20. It is *not* a model - it is only a summary of a local example that could, in the future, be re-distilled with local examples from other areas to produce a general facies model. In the Battery Point summary sequence, we identified a channel-floor lag overlain by poorly defined trough cross-bedding (Facies A, Fig. 20). The in-channel deposits consisted of well-defined trough cross-bedding (B) and large sets of planar-tabular cross-bedding (C) that commonly showed a large paleocurrent divergence from the trough cross-bedding (Figs. 14 and 20; Cant and Walker, 1976, Fig. 7). The bar-top* deposits consisted mainly of small sets of planar-tabular cross-bedding (D), and the thin record of vertical accretion included cross-laminated siltstones interbedded with mudstones (F), and some enigmatic low-angle cross-stratified sandstones (G).

Upon developing this summary sequence, our first reaction was to compare it to the existing fluvial (meandering) norm (Fig. 2). Although both sequences showed channelled bases, followed by fining-upward sequences, there appeared to be sufficient differences that the norm would *not* act reliably as a basis for interpretation (Walker, "General Introduction" to this volume). In other words, the meandering model of Figure 2 seemed

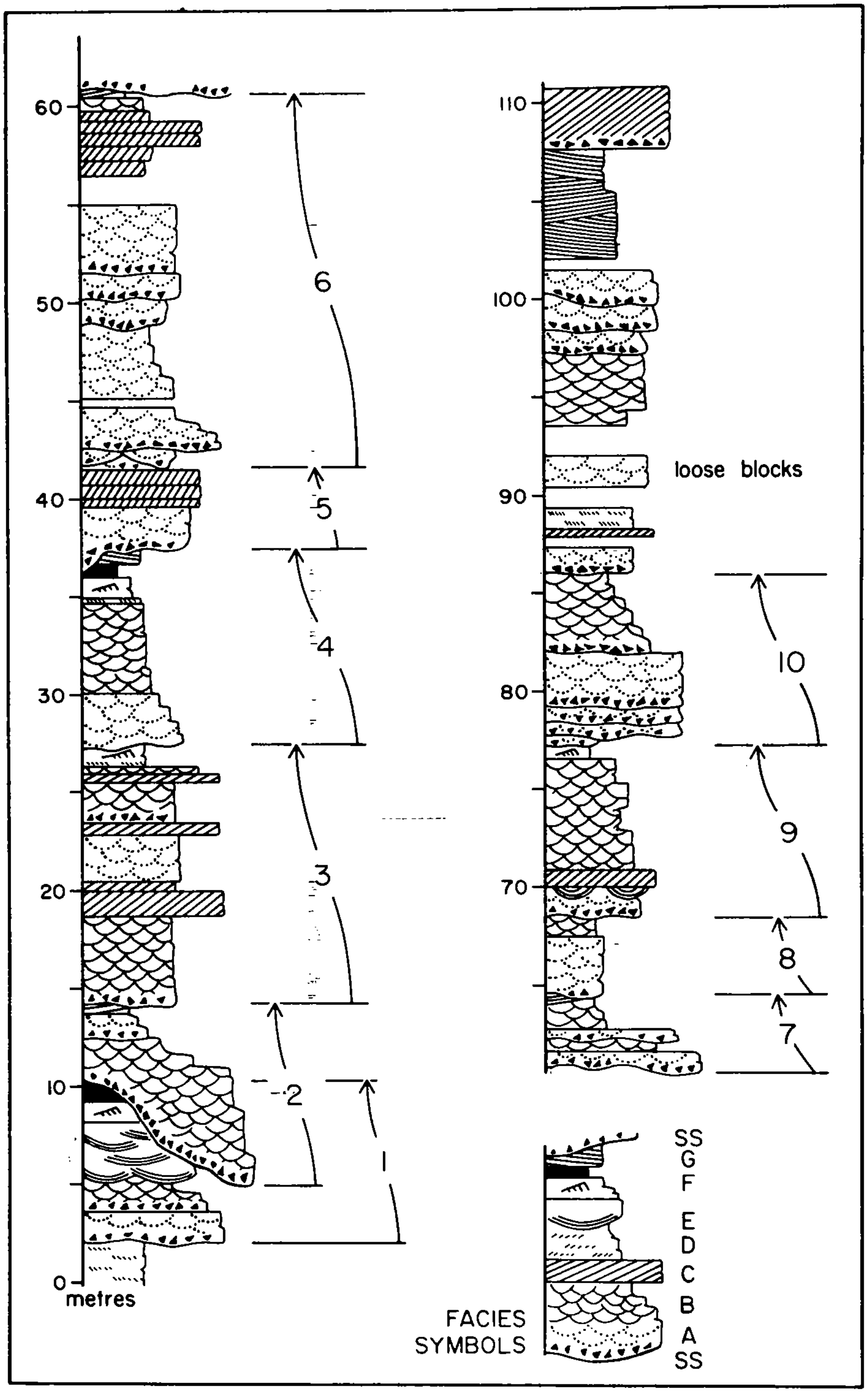


Figure 19
Measured section of the Devonian Battery Point Sandstone, Quebec (from Cant and Walker, 1976). Numbers indicate individual fluvial sequences, and letters define facies: SS = scoured surface; A = poorly-defined trough cross bedding; B = well-defined trough cross bedding; C = large planar tabular cross beds; D = small planar tabular cross beds; E = isolated scour fills; F = ripple cross laminated silts and muds; and G = low angle inclined stratification.

inappropriate for the Battery Point Sandstone of Figure 20.

Comparison with the norm nevertheless highlighted the major differences, and this gave us added understanding of the Battery Point. Similar comparisons of other systems with the squences in Figures 2 and 20 should also give added understanding. For example, the vertical-accretion deposits in the Battery Point are very thin compared with the meandering norm, both in absolute terms, and in proportion to the amount of in-channel sandstone. The in-channel sandstones do not contain parallel lamination, but planar-tabular sets of cross-bedding are common, and show high paleocurrent divergences from the main channel trend. All of these points of comparison aided in making our "braided" interpretation (Cant and Walker, 1976, p. 115-118). Refer also to annotated comments on the paper by Campbell (1976) in references.

Allen (1983) has interpreted the Devonian Brownstones of Wales as a series of sandy braided stream deposits. These are organized into a series of hierarchical units contained within intraclast-strewn scour surfaces. The 2 to 5 m thick units consist of parallel laminated and trough and planar cross-bedded sandstones and minor conglomerate. Traced laterally, the vertical sequence of sedimentary structures in each unit is extremely variable. The most striking aspect of these units is the almost ubiquitous inclination of planar cross-bed sets. Allen (1983) interprets this as slipface-bounded bars (Fig. 21) accreting laterally onto sandflats in a South Saskatchewan-like mechanism (Fig. 22). This study documents dramatically in 11 long profiles how much local lateral variability we should expect to find in braided stream sequences, as implied in studies of modern streams such as the South Saskatchewan.

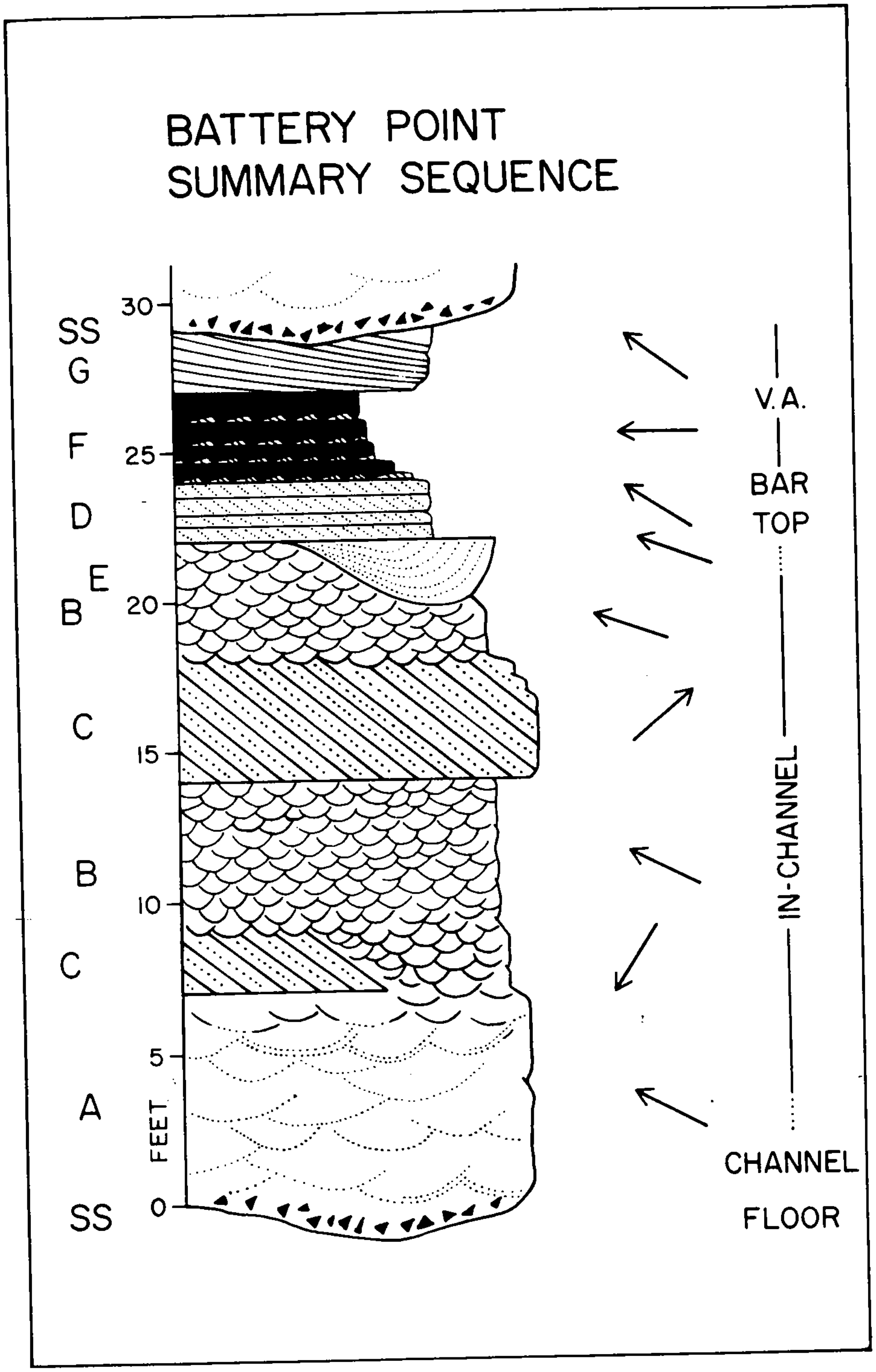


Figure 20
Summary sequence for the Devonian Battery Point Sandstone, Quebec. This sequence was developed by Markov analysis of the facies relationships (see "General Introduction" to this volume), and the preferred facies relationships were drawn as a stratigraphic column using average facies thicknesses. Arrows show paleoflow directions, letters indicate facies (see Cant and Walker, 1976). Compare the Battery Point system, interpreted as braided, with the South Saskatchewan (Fig. 17) and with Allen's (1970) sequence for meandering rivers (Fig. 2).

Sand Body Geometry And Flood-Plain Aggradation

One major point of contrast with the meandering system is that braided rivers tend to have easily erodible banks, and no clay plugs. The area occupied by the braided river may therefore be very wide (see Campbell, 1976), and coalescing bars and sandflats will result in a laterally continuous and extensive sand sheet unconfined by shales (Fig.

9B). Vertical accretion deposits (if formed) will tend to be quickly eroded because of the comparatively rapid lateral migration of channels. Consequently, any shales preserved in the section will tend to be patchy, laterally discontinuous, and relatively ineffective barriers to vertical hydrocarbon migration. This will not be the case for meandering systems.

Anastomosed Rivers

During the last five years, the anastomosed river has emerged as a type distinct from braided and meandering (Smith and Smith, 1980; Smith and Putnam, 1980; Putnam and Oliver, 1980; Putnam, 1982a; Smith, 1983). There are relatively few documented examples of modern anastomosed rivers (see Smith, 1983), and even fewer ancient examples (see Putnam and Oliver, 1981 and the discussion of this paper by Wightman *et al.*, 1981).

Smith and Smith (1980, p. 157) "use the term anastomosed river for an interconnected network of low-gradient, relatively deep and narrow, straight to sinuous channels with stable banks composed of fine-grained sediment (silt/clay) and vegetation . . . separating the channels are floodplains consisting of vegetated islands, natural levees, and wetlands".

Such streams differ from braided sandy rivers by having stable channel patterns and abundant areas in which fine-grained sediment is deposited and preserved.

Depositional Environments In Anastomosed Systems

Smith and Smith (1980) recognized six main facies in gravelly anastomosed rivers in western Canada (Mistaya, Alexandra, North Saskatchewan, in Alberta).

1) Peat bog facies, containing up to 98% vegetal matter, in layers a few cm to 1.5 m thick.

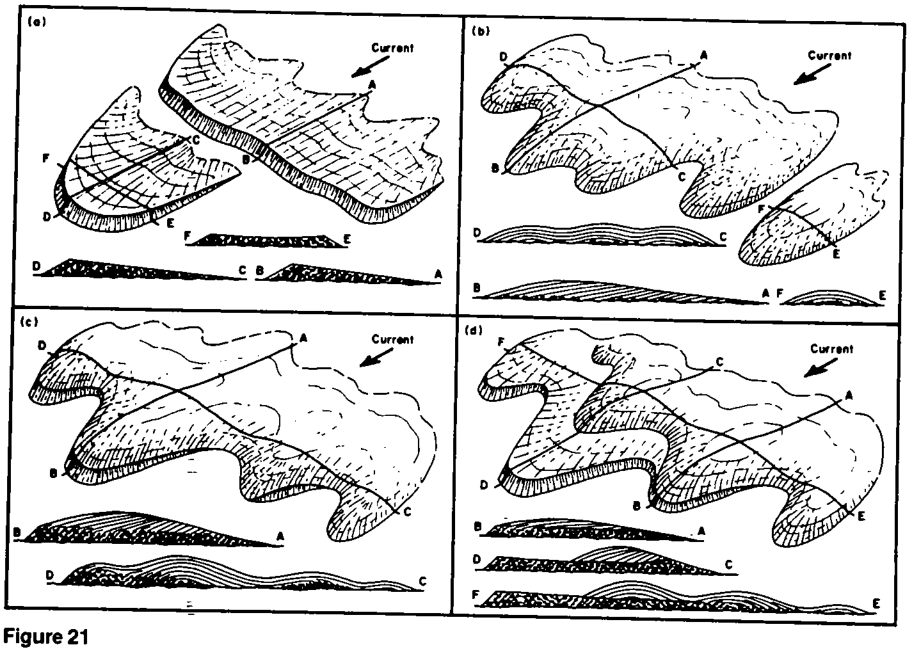


Figure 21
Superb outcrops in the Welsh Borderlands allowed Allen (1983) to reconstruct these four bar types for the Devonian Brownstones. A - cross bedded simple bars; B - plane bedded *simple bars; C -* a compound bar; D - a composite compound bar.

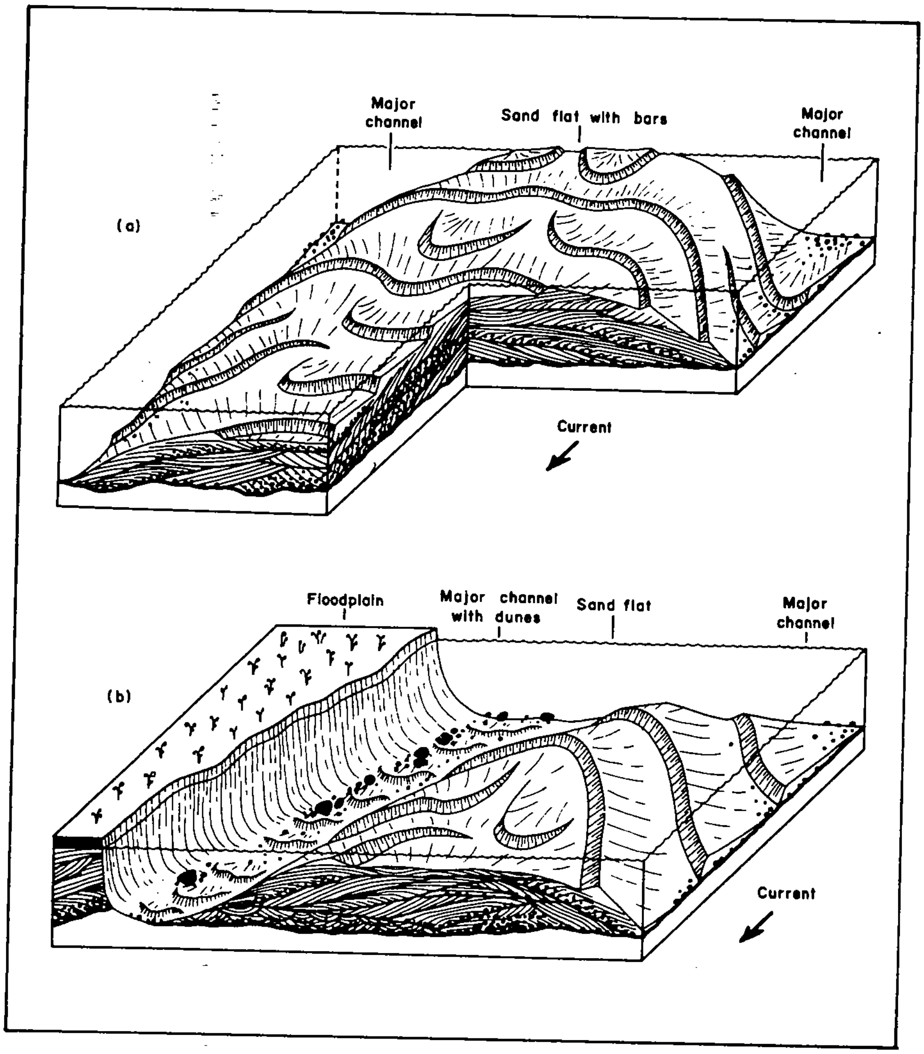


Figure 22
Local facies models for sheet sandstones in the Devonian Brownstones, Welsh Borderlands, from Allen (1983). A - wide sand flat; minor channels related to falling stage may be expected to cross the top of the flat but are not shown. B - proximal part of a sand flat and its structure in strike section, together with a major channel and adjacent flood plain (vegetated island, valley flat). Vertical scales greatly exaggerated in both diagrams.

2) Backswamp facies, composed of silty mud or muddy silt, with variable amounts of organic debris.
3) Floodpond facies, consisting of laminated clay and silty clay with sparse vegetal material. Thickness is up to 6 m.
4) Levee facies, consisting of sandy silt and silty sand containing 10-22% roots by volume. This facies grades into the wetland facies (peat bog, backswamp and floodpond).
5) Crevasse splay facies, making up less than 5% of the vertical accretion facies (1 to 5, above), and consisting of thin layers of sand and/or fine gravel.
6) Channel facies, consisting of gravel and coarse sand, of unknown thickness due to limitations of augering.

These environments are controlled by a rapidly elevating base level at the downstream end of the anastomosed system, causing high rates of aggradation, deposition of fines, and stabilization of river channel patterns. In the geological record, thick vertically accreted sand bodies bounded by wetland facies would be predicted, and a block diagram emphasizing channel confinement and lack of lateral accretion is given in Figure 23. It is emphasized that the data base for this block diagram consists of augered holes a little more than 10 m deep; the aggradational history of these systems is not yet fully documented.

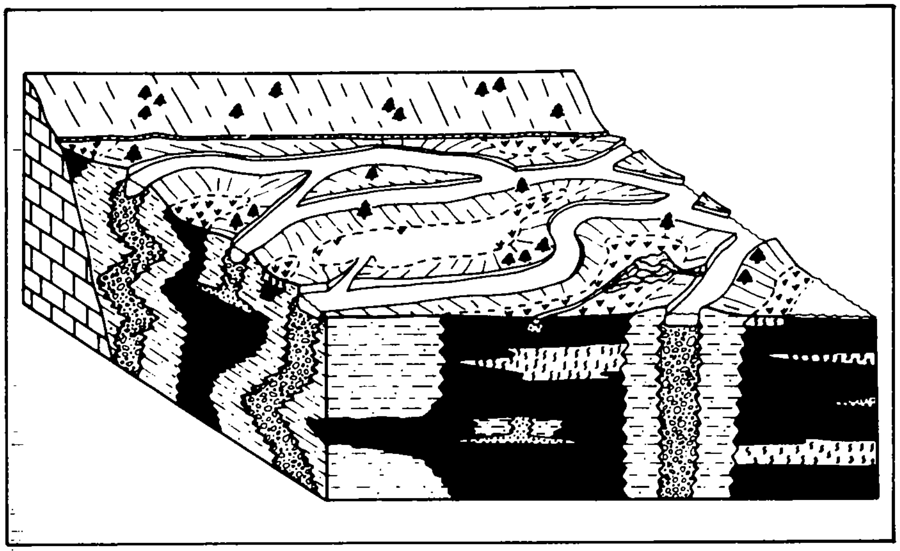


Figure 23
Block diagram of an anastomosed river, from Smith and Smith (1980). In this typical reach, channel sediments (gravel symbol) are bounded by sandy silt (dash, dot symbol) of the levees, which in turn grade into muds and silty muds of the wetlands (black). Peats are shown by small vertical wiggles. Note channel aggradation without significant lateral accretion, the channel pattern being stabilized by the muds and organic material of the wetlands, which are hard to erode.

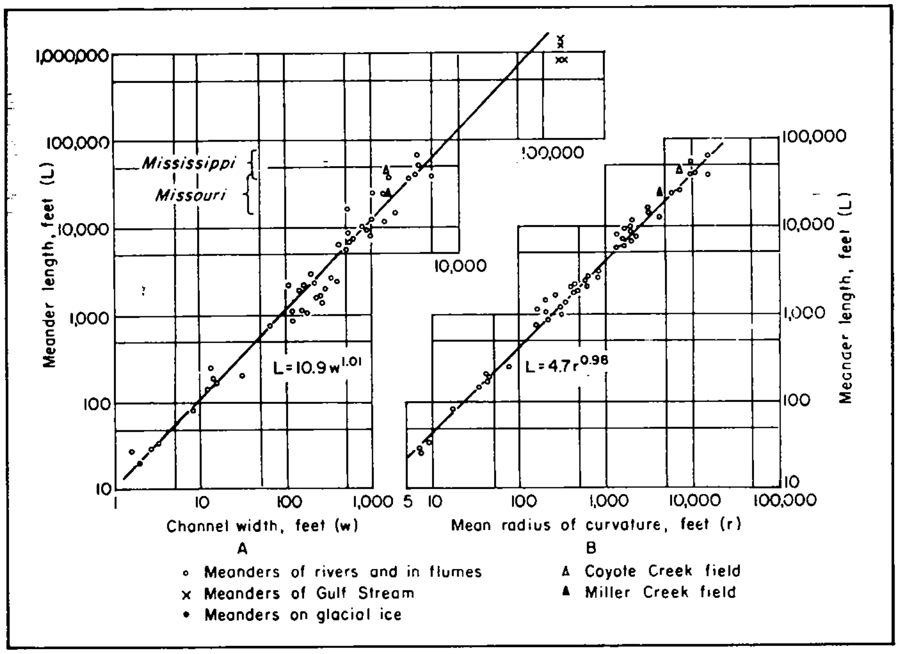


Figure 24
Relationships between meander length, channel width and meander loop radius of curvature. Original data for modern meandering streams from Leopold and Wolman (1960), with Coyote Creek and Miller Creek data plotted by Berg (1968). Note that both Coyote Creek and Miller Creek lie about as far from the regression line as any of the data, suggesting that these two fields differ somewhat from the meandering river "norm", which is represented by the regression line. From Berg (1968).

Ancient Anastomosed Systems

The only ancient system interpreted to be anastomosed is part of the Upper Mannville Group (Albian) of east-central Alberta (Putnam and Oliver, 1980; Putnam, 1980; Putnam, 1982a, 1982b). Here, a pattern of branching and rejoining channels has been illustrated (although it is not clear that all of the channels shown are exactly contemporaneous), and channel sandstones up to 35 m thick can be seen in cores and well-logs. Between the channel sands are "siltstones, shales, coals, and thin (generally less than 6 m thick) sheet-like sandstones which pinch out with increasing distance from the main channel fill" (Putnam, 1982a, p. 438). Some of the ideas and data presented by Putnam and Oliver (1980) have been challenged by Wightman *et al.* (1981), with a reply by Putnam and Oliver (1981). It seems clear that it is premature to propose a general anastomosed fluvial *model* on the basis of so few modern and ancient examples. However, it is important to bear in mind that this type of stream may help to explain or interpret as-yet-undescribed ancient examples that do not fit braided or meandering norms.

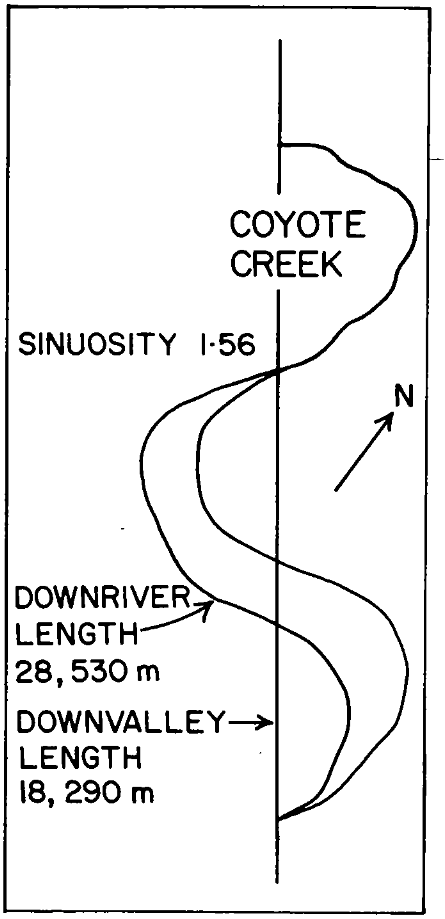


Figure 25

Extrapolation of Coyote Creek meander loop. Assuming a downvalley direction, a downvalley length of 18,290 m (60,000') was plotted. The calculated sinuosity is 1.56 (see text), so the equivalent downriver length is 28,530 m. Two possible river patterns are shown southeast of the Coyote Creek loop – many other patterns are possible, and can be estimated using a scale length of string laid over the diagram and bent into appropriate meander patterns. Details in text.

Fluvial Geomorphological Models And Paleohydraulic Reconstructions

There appears to be a direct and predictable relationship between many meandering river parameters, such as channel width (W), depth (D), sinuosity (P), meander wavelength (L), meander radius (R), slope (S) and mean annual discharge (Q). These relationships were developed by geomorphologists (especially Schumm and Leopold; references in Miall, 1978 and Ethridge and Schumm, 1978), and can be expressed by a series of regression equations (Fig. 24).

The regression equations state in a general way the relationship between parameters based on a large number of examples – that is, the regression lines are *norms*. The equations are likewise *predictors*, but beyond here, the analogy with facies models breaks down. The regression lines are not guides for future observations, nor can they be used as a basis for interpretations.

Earlier in this paper, we discussed the Coyote Creek subsurface point bar (Berg, 1968). Channel depth (roughly equal to point bar thickness) can be estimated at about 23 m (Fig. 10), and channel width (about 460 m), radius of curvature (about 2130 m) and meander length (about 12,200 m) can be estimated from Figure 11. It is important to see whether the Coyote Creek example lies close to the norm – if it does, it can be considered "typical", and one might have some confidence in using other regression equations. However, note in Figure 23 that the Coyote Creek data point lies far from the regression lines, implying that it does *not* closely resemble the "norm". The following calculations involve comparisons of Coyote Creek parameters with various other norms, and hence the results may not be too reliable. They are given here simply to illustrate the possibilities.

Mean annual discharge is estimated by

$$Q = W^{2.43}/18\ F^{1.13} \text{ (Imperial units)} \qquad (1)$$

where F is the width/depth ratio (here 460/23 = 20). The discharge of the Coyote Creek river is thus estimated as 98,280 cubic feet/second, or 2783 m^3/sec.

Sinuousity P is given by

$$P = 3.5\ F^{-0.27} \text{ (Imperial Units)} \qquad (2)$$

and works out to 1.56. This number could be very useful in predicting the position and size of the next meander loop upstream or downstream from Coyote Creek, which is of obvious significance in exploration for hydrocarbons; this prediction is attempted in Figure 25, again for the sole purpose of illustrating *how* a model can be used in prediction.

The reconstructed meander loops in Figure 25 were drawn in the following way:

1) using a downvalley distance of 60,000 feet, the river length is simply 60,000 x sinuousity = 93,600 feet (28,530 m),
2) a piece of string scaled to 93,600 feet was placed over the Coyote Creek meander loop. Its far end was placed at a downvalley distance of 60,000 feet, thus defining the rough size and position of the second and third meander loops,
3) apart from problems of whether it is valid to reconstruct Coyote Creek using the meandering river norm (Fig. 24), note that we also do not know the downvalley paleoslope orientation. We also assume that the Coyote Creek meander loop (Fig. 11) is of average size for this reach of the river, because the downriver distance used to measure sinuosity in the field should normally be taken through as many meanders as possible, not just one.

Meander wavelength (L) is estimated by

$$L = 18\ (F^{0.53}\ W^{0.69}) \text{ (Imperial units)} \qquad (3)$$

and is about 13,687 feet (4172 m).

In Figure 11, note that the estimated meander wavelength is actually 40,000 feet (12,192 m), very different from the 13,687 feet calculated above. There are at least three possible reasons for this discrepancy; 1) Coyote Creek is so different from the norm that this type of analysis is not valid; 2) the channel width has been underestimated, and is closer to 2000 feet (610 m) (Berg, 1968, p. 151); and 3) the point bar thickness is closer to 50 feet (15 m) and the 75 foot (23 m) isopachs represent unusually deep channel floor scours during lateral accretion of the point bar (Fig. 11). Thus with W = 2000 feet and D = 50 feet, equation (2) gives a sinuosity of 1.29 and equation (3) gives a value for L of 24,103 feet (7347 m). This is still much less than the 40,000 feet estimated in Figure 11, and suggests that the Coyote Creek river is too far from the meandering river norm (Fig. 24) for this type of analysis to be valid. The reader can pursue this problem by trying to reconstruct meander loops in Figure 25 using P = 1.29 and L = 24,103 feet.

CONCLUSIONS

The meandering model seems well established and is reasonably well understood. It is a good example of a facies model in that the relationships shown in a block diagram (Fig. 1) are well known from ancient and recent sediments. Also, the simplest vertical facies sequence (Fig. 2) is well established by Markov analysis. Furthermore, numerical predictions based on channel patterns may be possible using a series of regression equations - the equations themselves are a form of model.

Braided streams have a much smaller data base, both in recent and ancient sediments. There are few well-established ancient examples, and there appear to be no convincing and well-documented subsurface examples. Anastomosed systems are even less well understood, and the only proposed ancient example is somewhat controversial.

REFERENCES

BASIC READING

The papers cited here are all listed in the alphabetic reference list below. General review papers include those of Collinson (1978) and Cant (1982). The first papers to consult on meandering streams would probably be Allen (1965, 1970) and Jackson (1976); on braided sandy streams one should begin with Allen (1983) and Cant and Walker (1976, 1978). Miall's (1977) review of the braided system is also very useful, but considers gravelly systems as well as sandy ones.

For a historical review, the most useful paper is that of Miall (1978a), and for papers on exploration, and the subsurface significance of fluvial models, see Horne *et al.* (1978), Berg (1968), Hopkins *et al.* (1982) and Putnam (1982a, 1983).

There are three recent collections of papers which, although written at the technical research level, give an unsurpassed entry into the fluvial literature - see Miall (ed., 1978b), Collinson and Lewin (eds., 1982), and Ethridge and Flores (eds., 1981).

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Campbell, C.V., 1976. Reservoir geometry of a fluvial sheet sandstone. American Association of Petroleum Geologists, Bulletin, v. 60, p. 1009-1020.
Describes lateral extent of sandbodies in part of the Morrison Formation. Proposes a sequence of structures that is dominated by trough cross bedding, and hence one that is very different from the South Saskatchewan sequences.

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Collinson, J.D., and Lewin, J., eds., 1982. Modern and ancient fluvial systems. International Association of Sedimentologists, Special Publication 5, 535 p.
Very useful collection of papers, grouped into sections on Hydrodynamics and Bedforms, Present Day Channel Processes, Facies Models, and Economic Aspects. A very useful source of data and references.

Conaghan, P.J., and Jones, J.G., 1975. The Hawkesbury Sandstone and the Brahmaputra: a depositional model for continental sheet sandstones. Journal of the Geological Society of Australia, v. 22, p. 275-283.
Proposes a braided fluvial origin for the Hawkesbury, and gives an idealized vertical sedimentary structure sequence.

Doeglas, D.J., 1962. The structure of sedimentary deposits of braided rivers. Sedimentology, v. 1, p. 167-190.
Classic descriptions of the Durance and Ardeche Rivers in France. The paper has perhaps been overlooked in the last few years because it does not present overall sedimentary structure sequences - nevertheless, the descriptions remain extremely useful.

Dixon, E.E.L., 1921. The geology of the South Wales coalfield; Part XII: the country around Tenby. Geological Survey of Great Britain, Memoir.
In this paper, the repetitive nature of what we now call a fining-upward sequence was recognized and stated more clearly than by Barrell. This paper, therefore, contains the first explicit statement of repetitive, superimposed fluvial sequences.

Edwards, M.B., Eriksson, K.A., and Kier, R.S., 1983. Paleochannel geometry and flow patterns determined from exhumed Permian point bars in north-central Texas. Journal of Sedimentary Petrology, v. 53, p. 1261-1270.
Reconstruction of flow associated with obliquely-oriented ripples on point bar surfaces.

Ethridge, F.G., and Flores, R.M., eds., 1981. Recent and ancient nonmarine depositional environments: models for exploration. Society of Economic Paleontologists and Mineralogists, Special Publication 31, 349 p.
Contains a series of papers, written at the full technical level, grouped into: 1) recent and ancient nonmarine depositional models; 2) alluvial fan and fluvial deposits; 3) lacustrine deposits; and 4) eolian deposits.

Ethridge, F.G. and Schumm, S.A., 1978. Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations and assessment. *In* Miall, A.D., ed., Fluvial sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, p. 703-721.
A very useful summary of paleohydraulic reconstruction methods, with all assumptions spelled out, and equations and their sources given.

Fisk, H.N., 1944. Geological investigation of the alluvial valley of the lower Mississippi River. Vicksburg, Miss., Mississippi River Commission, 78 p.
A classic description of the river pattern of the lower reaches of the Mississippi.

Frazier, D.E., and Osanik, A., 1961. Point bar deposits, Old River locksite, Louisiana. Gulf Coast Association of Geological Societies, Transactions, v. 11, p. 121-137.
One of the first large excavations within a fluvial system, with discussions of the geometry of stratification.

Harms, J.C., and Fahnestock, R.K., 1965. Stratification, bed forms and flow phenomena (with an example from the Rio Grande). *In* Middleton, G.V., ed., Primary sedimentary structures and their hydrodynamic interpretations. Society of Economic Paleontologists and Mineralogists, Special Publication 12, p. 84-115.
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Harms, J.C., Mackenzie, D.B., and McCubbin, D.G., 1963. Stratification in modern sands of the Red River, Louisiana. Journal of Geology, v. 71, p. 566-580.
One of the first descriptions of the internal structure of point bars, emphasizing the development of stratification from bed forms.

Harms, J.C., Southard, J.B., and Walker, R.G., 1982. Structures and sequences in clastic rocks. Society of Economic Paleontologists and Mineralogists, Short Course 9, variable pagination.
Revised version of Short Course 2, with important introductory chapters by Southard and Harms on flow, bed forms and stratification.

Haszeldine, R.S., 1983. Fluvial bars reconstructed from a deep, straight channel, Upper Carboniferous coalfield of northeast England. Journal of Sedimentary Petrology, v. 53, p. 1233-1247.
Excellent and detailed reconstruction of the internal form of stratification within a bar 10 m high and 200 m wide. Lobate sandwaves 20 m wide descended the lee face of the bar.

Hopkins, J.C., Hermanson, S.W., and Lawton, D.C., 1982. Morphology of channels and channel-sand bodies in the Glauconitic Sandstone Member (Upper Mannville), Little Bow area, Alberta. Bulletin of Canadian Petroleum Geology, v. 30, p. 274-285.
Reconstruction of channel patterns from subsurface data. See Figures 12 and 13 of this paper. Well logs supported by core photographs.

Horne, J.C., Ferm, J.C., Caruccio, F.T., and Baganz, B.P., 1978. Depositional models in coal exploration and mine planning in Appalachian region. American Association of Petroleum Geologists, Bulletin, v. 62, p. 2379-2411.
An excellent and well illustrated study of how fluvial (and marginal marine) models can be used in exploration.

Jackson, R.G., 1976. Depositional model of point bars in the lower Wabash River. Journal of Sedimentary Petrology, v. 46, p. 579-594.
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Describes two types of vertical stratification sequence, and interprets the Rhondda beds as having been deposited both from low and high sinuosity streams.

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Very useful descriptions of the Amite (La.) and Colorado (Tx.) Rivers, and comparisons with Eocene and Pleistocene deposits. Stratification and internal structure sequences emphasized.

Miall, A.D., 1973. Markov chain analysis applied to an ancient alluvial plain succession. Sedimentology, v. 20, p. 347-364.
Applies Markov chain analysis to Devonian fluvial rocks in arctic Canada, and proposes a test of significance for the probability matrices as a whole. Harper's method tests each entry in the matrix (see "Improved Methods of Facies Sequence Analysis" in this volume).

Miall, A.D., 1977. A review of the braided river depositional environment. Earth Science Reviews, v. 13, p. 1-62.
Miall reviews sandy and gravelly braided systems, and proposes a standard set of facies for their description. Distillation of these facies into sequences suggests four main types - the Scott, Donjek, Platte and

Bijou Creek. Others have been added subsequently (see Miall, 1978b).

Miall, A.D., 1978a. Fluvial sedimentology: an historical review. *In* Miall, A.D., ed., Fluvial sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, p. 1-47.
Undoubtedly the most thorough historical review of fluvial sedimentology, beginning with observations in prehistoric times and continuing to the present day. An invaluable source for older references.

Miall, A.D., ed., 1978b. Fluvial sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, 859 p.
Collection of many papers, written at the technical research level, and grouped into Texture and Structure, Bedforms and Bars, Modern Rivers, Ancient Fluvial Systems, Fluvial Facies Models, Paleohydraulics, and Economic Applications. Overall an extremely useful source of data and references.

Moody-Stewart, M., 1966. High- and low-sinuosity stream deposits, with examples from the Devonian of Spitsbergen. Journal of Sedimentary Petrology, v. 36, p. 1102-1117.
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Putnam, P.E., 1982b. Fluvial deposits and hydrocarbon accumulations: examples from the Lloydminster area, Canada. *In* Collinson, J.D., and Lewin, J., eds., Modern and ancient fluvial systems. International Association of Sedimentologists, Special Publication 6, p. 517-532.
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Putnam, P.E., and Oliver, T.A., 1980. Stratigraphic traps in channel sandstones in the upper Mannville (Albian) of east-central Alberta. Bulletin of Canadian Petroleum Geology, v. 28, p. 489-508.
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Authors reply here to the criticisms of Wightman *et al.* (1981).

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Smith, D.G., and Putnam, P.E., 1980. Anastomosed fluvial deposits: modern and ancient examples from Alberta, Canada. Canadian Journal of Earth Sciences, v. 17, p. 1396-1406.
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Wightman, D.M., Tilley, B.J., and Last, W.M., 1981. Stratigraphic traps in channel sandstones in the upper Mannville (Albian) of east-central Alberta: Discussion. Bulletin of Canadian Petroleum Geology, v. 29, p. 622-625.
Criticism of Putnam and Oliver's (1980) paper, questioning the application of the anastomosed model to the Upper Mannville, and questioning the validity of the channel sandstone trends. See reply by Putnam and Oliver (1981).