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Anastomosing rivers: a review of their classification, origin and sedimentary products

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Abstract

Anastomosing rivers constitute an important category of multi-channel rivers on alluvial plains. Most often they seem to form under relatively low-energetic conditions near a (local) base level. It appears to be impossible to define anastomosing rivers unambiguously on the basis of channel planform only. Therefore, the following definition, which couples floodplain geomorphology and channel pattern, is proposed in this paper: *an anastomosing river is composed of two or more interconnected channels that enclose floodbasins*. This definition explicitly excludes the phenomenon of channel splitting by convex-up bar-like forms that characterize braided channels.

In present definitions of anastomosing rivers, lateral stability of channels is commonly coupled with their multi-channel character. Here, it is suggested that these two properties be uncoupled. At the scale of channel belts, the terms 'straight', 'meandering' and 'braided' apply, whereas at a larger scale, a river can be called anastomosing if it meets the definition given above. This means that, straight, meandering and braided channels may all be part of an anastomosing river system. Straight channels are defined by a sinuosity index; i.e., the ratio of the distance along the channel and the distance along the channel-belt axis is less than 1.3. They are the type of channel that most commonly occurs in combination with anastomosis. The occurrence of straight channels is favoured by low stream power, basically a product of discharge and gradient, and erosion-resistant banks.

Anastomosing rivers are usually formed by avulsions, i.e., flow diversions that cause the formation of new channels on the floodplain. As a product of avulsion, anastomosing rivers essentially form in two ways: (1) by formation of bypasses, while bypassed older channel-belt segments remain active for some period; and (2) by splitting of the diverted avulsive flow, leading to contemporaneous scour of multiple channels on the floodplain. Both genetic types of anastomosis may coexist in one river system, but whereas the first may be a long-lived floodplain-wide phenomenon, the latter only represents a stage in the avulsion process on a restricted part of the floodplain.

Long-lived anastomosis is caused by frequent avulsions and/or slow abandonment of old channels. Avulsions are primarily driven by aggradation of the channel belt and/or loss of channel capacity by in-channel deposition. Both processes are favoured by a low floodplain gradient. Also of influence are a number of avulsion triggers such as extreme floods, log and ice jams, and in-channel aeolian dunes. Although some of these triggers are associated with a specific climate, the occurrence of anastomosis is not. A rapid rise of base level is conductive to anastomosis, but is not a necessary condition.

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Anastomosing rivers can be considered an example of equifinality, since anastomosis may result from different combinations of processes or causes.

Anastomosing river deposits have an alluvial architecture characterized by a large proportion of overbank deposits, which encase laterally connected channel sand bodies. Laterally extensive, thick lenses of lithologically heterogeneous, fine-grained avulsion deposits can be an important element of the overbank deposits of anastomosing rivers. These deposits may also fully surround anastomosing channel sandstones. Anastomosing channel sand bodies frequently have ribbon-like geometries and may possess poorly developed upward-fining trends, as well as abrupt flat tops. The overbank deposits commonly comprise abundant crevasse splay deposits and thick natural levee deposits. Lacustrine deposits and coal are common in association with anastomosing river deposits. None of these characteristics is unique to anastomosing river deposits, and in most cases, anastomosis (coexistence of channels) cannot be demonstrated in the stratigraphic record.

Keywords: anastomosing rivers; straight rivers; channel pattern; floodplains; fluvial sedimentation; avulsion

1. Introduction

Anastomosing rivers represent a major group of rivers that are currently of interest in fluvial geomorphology and sedimentology. For a long time, they were frequently confused with braided rivers, which roughly have a comparable planform. Nowadays, the term ‘anastomosing’ is reserved for a type of river with multiple, interconnected, coexisting channel belts on alluvial plains (Fig. 1), which most often seems to form under relatively low-energetic conditions near a local base level.

In past three decades, a substantial number of anastomosing river systems has been reported worldwide (e.g. Smith, 1973, 1983, 1986; Smith and Smith, 1980; Rust, 1981; Nanson et al., 1986; Schumann, 1989; Schumm et al., 1996; Makaske, 1998; and many others). It is realized now that ancient anastomosing river deposits may have a high preservation potential in the stratigraphic record, and that they can have much economic importance (Smith and Putnam, 1980; Putnam, 1993; Smith, 1986). Modern anastomosing river floodplains provide an extensive potential of arable and pasture land for rapidly growing populations in developing countries (e.g. Makaske, 1998, p. 245). Putting this potential into use requires control measures in the natural river system to prevent flooding and to restrain channel

Fig. 1. The anastomosing Tonlé Sap River in central Cambodia.

dynamics. In addition, some anastomosing river floodplains support rare and diverse ecosystems that need conservation. Thus, continued scientific attention to the origin and evolution of anastomosing river systems is needed.

In spite of the accumulating number of studies on anastomosing rivers, major controversies still exist about their definition, the causes for their existence, and the significance of anastomosing river facies models. Multiple incongruous criteria have been used by different authors for definition of the anastomosing river type. What also remains unclear is the relationship between anastomosing rivers and distributary river deltas, and the relationship between anastomosing rivers and straight rivers (sensu Schumm and Khan, 1972). Considering the causes of river anastomosis, controversies concern the roles of climate, base level, and floodplain sedimentation rates. Modern anastomosing rivers have been reported from various climatic zones; however, certain controls of anastomosis (especially vegetation) seem to differ with climate. Are morphologically similar anastomosing rivers in different climates a product of convergence [or equifinality (Schumm, 1988), with different processes or causes producing similar results? Apart from climate, the influences of base level and floodplain sedimentation rates are unclear. Rapid base-level rise and high floodplain sedimentation rates have been mentioned as prime causes for anastomosis in modern examples from western Canada and Colombia (Smith, 1983, 1986). In contrast, in central Australia anastomosing rivers exist under relatively low floodplain sedimentation rates, resulting from a relatively stable base level (Rust, 1981; Nanson et al., 1986; Gibling et al., 1998). Also, the universal applicability of anastomosing river facies models is not generally agreed upon. Reviewing fluvial facies models, Hickin (1993, p. 210) even suggested that: "... the 'anastomosing river facies model' is an entirely premature concept, the full development of which should await much more extensive field studies of modern rivers".

In this paper, the state of our knowledge of anastomosing rivers in alluvial settings is evaluated, focusing on their geomorphology as well as on their sedimentology. Both modern and interpreted ancient examples are reviewed. The three main questions addressed in this paper are: (1) when to call a river 'anastomosing'; (2) what drives river anastomosis; and (3) what are sedimentary products preserved of an anastomosing river system on a geological time scale?

In the first part of this paper, I propose a geomorphological definition and classification of anastomosing rivers. In the second part, processes and external controls of modern and subrecent anastomosing rivers are reviewed. This leads to a conceptual model for the origin of anastomosing rivers. In the third part, the sedimentary products of modern and ancient anastomosing rivers are discussed and criteria useful for the identification of ancient anastomosing river systems are proposed.

2. Definition and classification

2.1. Introduction

Schumm (1968, p. 1580) may have been the first to point out that the term 'anastomosing' should not be used as a synonym for braiding: "The terms braiding and anastomosing have been used synonymously for braided river channels in this country, but elsewhere, particularly in Australia, anastomosing is a common term applied to multiple-channel systems on alluvial plains (...). The channels transport flood waters and, because of the small sediment load moved through them, aggradation, if it is occurring, is a slow process. As a result, these low-gradient suspended-load channels are quite stable (...)." Although Schumm's description seems to be a clear starting point, nowadays there is a bewildering array of definitions of the anastomosing river type.

Preferably, a definition of a river type should meet the following criteria: (1) It should be workable in the sense that an air-photo interpretation or a quick field survey should be sufficient to enable its application. Therefore, it should not include genetic, hydraulic or sedimentological characteristics, but instead it should be based on a limited number of visual characteristics concerning channel pattern and floodplain geomorphology. (2) It should be useful in the sense that it distinguishes a group of rivers with a similar genesis and similar sedimentological and hydraulic characteristics.

2.2. Channel pattern

Following work of the past two or three decades, it is now generally accepted that an anastomosing river is a multi-channel river which is fundamentally different in form and process from a braided river. Can this river type be defined on the basis of channel pattern?

A channel pattern is considered as a two-dimensional, planform configuration only, regardless of any other floodplain characteristics. In this respect, two properties are most relevant: (a) channel sinuosity (distance along the channel divided by straight line distance) and (b) channel multiplicity.

Rust (1978) defined anastomosing rivers as: high-sinuosity (>1.5), multi-channel rivers. He applied sinuosity and the braiding parameter (number of braids per mean meander wavelength) to distinguish between straight, braided, meandering and anastomosing (Table 1). He admitted that his boundary values were arbitrary, but stated that a classification should be quantitative. Rust (1981, his table 2) listed mean sinuosities of anastomosing rivers ranging from 1.51 to 1.75. Smith (1983), however, described anastomosing rivers in western Canada and found low sinuosities (1.16 and 1.4). He concluded that anastomosing rivers have variable sinuosities (Smith and Putnam, 1980). So it seems that sinuosity of the individual branches is not suitable for distinguishing anastomosing rivers (see also Table 2), a fact also recognized by Knighton and Nanson (1993).

Yonechi and Maung (1986) pointed out that braided channels bifurcate at acute angles to the main flow direction, while anastomosing channels bifurcate at a wider range of angles and even at obtuse angles. Harwood and Brown (1993) also noted the relatively large angles of bifurcation of anastomosing channels. The angle of bifurcation reflects a difference between the mechanisms leading to braiding (formation of mid-channel bars) vs. anastomosis (avulsion, see Section 3.2). However, the differences in bifurcation angles between braiding and anastomosing are too small to serve as a basis for a clear-cut definition [see for example Yonechi and Maung (1986, their fig. 5)].

Table 1
Classification of channel patterns according to Rust (1978)

	Single-channel (braiding parameter <1)	Multi-channel (braiding parameter <1)
Low-sinuosity ($P<1.5$)	straight	braided
High-sinuosity ($P<1.5$)	meandering	anastomosing

Knighton and Nanson (1993) stated that islands between anastomosing channels are large relative to the size of the channels. Some workers included a measure of the length or width of alluvial islands in the definition of the term anastomosing. In this context, the term *anabranching* has been frequently used. Bridge (1993, p. 21) stated that "... anastomosing channel segments (...) are longer than a curved channel segment around a single braid or point bar and their width-scale flow patterns behave substantially independent of the adjacent segments." He considered anabranching as a synonym of anastomosing. Brice et al. (1978) (in Schumm, 1985) used the term anabranching for channels enclosing islands having a width larger than three times channel width at average discharge. Schumm (1985) regarded anabranching rivers as being essentially braided rivers with large exposed bars in relation to channel width, as opposed to anastomosing rivers being true multi-channel systems. Nanson and Knighton (1996), however, considered anastomosing rivers as a subgroup of anabranching rivers. By them, anabranching rivers were not defined by the size of the alluvial islands or any other channel pattern characteristic, but by the stability of riverbanks (caused by vegetation or otherwise) and continued existence of the islands up to nearly bankfull stage. Anastomosing rivers were earlier classified as low-energy, anabranching rivers with cohesive banks (Smith and Smith, 1980; Rust, 1981).

In summary, present terminology is confusing and there is no consensus on how to incorporate the size of alluvial islands in a useful definition of anastomosis, although there is a tendency to consider anastomosing as a hierarchically higher order of channel pattern not comparable to straight, meandering and braided (e.g. Schumm, 1968, 1985; Bridge, 1993). This idea, however, is hard to translate into a definition based on channel pattern only. Boundary values for the size of islands tend to be quite arbitrary and

Table 2
Quantitative data on anastomosing rivers

River, climatic setting, and data source	Q_{ma} (m^3/s)	Q_{bf} (m^3/s)	Q_{max} (m^3/s)	S_{ch} (cm/km)	P (–)	w/d (–)	Sed. rate (mm/year)
Temperate humid							
Mistaya[1]		34		390		15	0.6
Alexandra[2]		66		60	1.51	13	1.8
North Saskatchewan[3]		164		100	1.62	16	1.8
Upper Columbia[4]	108	275	770	9.6	1.16	16	1.7
Lower Saskatchewan[5]	648	1400	3000	12.2	1.4[a]		1.5[b]
Ovens[6]		225		89	1.49	17	
Tropical humid							
Magdalena[7]	7400	8800		10.0		28	3.8
Japura[8]	11,130				1.1		
Solimões[9]	36,815				1.5		2.3
Magela Creek[10]		40	1580	50	1.1	10	1.5
Arid and semi-arid							
Red Creek[11]				11	1.92	< 10	
Upper Darling[12]	681	200		5	2.3	8	0.02
Cooper Creek[13]	40–100		5800–25,000	17.5	1.69	10	0.04
Fitzroy[14]			30,000	25	1.1	[c]	
Middle Niger[15]	1330		9700	2.0	1.2		0.14
Okavango[16]	335			19	1.5	≤ 20	
Subarctic							
Attawapiskat[17]	508		3115	52	< 1.5	70	[d]

Q_{ma} = mean annual discharge; Q_{bf} = bankfull discharge; Q_{max} = maximum recorded discharge; S_{ch} = channel slope; P = sinuosity; w/d = width/depth ratio of channels; Sed. rate = average floodplain sedimentation rate.

[a] P varies between ~1.1 for recent avulsion channels and 1.65 for old channels.
[b] Short-term sedimentation rates within the recent avulsion belt are up to 33 mm/year.
[c] w/d strongly variable: 6–233.
[d] Incision.
[1] Smith (1986), Smith and Smith (1980).
[2] Smith (1986), Smith and Smith (1980), Rust (1981).
[3] Smith (1973, 1986), Smith and Smith (1980), Rust (1981).
[4] Smith (1983, 1986), Water Survey of Canada (1991a), Makaske (1998).
[5] Smith (1983, 1986), Smith et al. (1989), Water Survey of Canada (1991b).
[6] Schumm et al. (1996).
[7] Smith (1986).
[8] Baker (1978).
[9] Baker (1978), Mertes (1994).
[10] Nanson et al. (1993), Knighton and Nanson (1993).
[11] Schumann (1989).
[12] Riley and Taylor (1978).
[13] Rust (1981), Knighton and Nanson (1993).
[14] Taylor (1999).
[15] ORSTOM (1970), Gallais (1967), Direction Nationale de l'Hydraulique et de l'Energie, Bamako, Mali (unpubl. data).
[16] McCarthy et al. (1991, 1992), Smith et al. (1997).
[17] King and Martini (1984).

not discriminative for a genetically, sedimentologically and hydraulically different type of river, since large islands can be coalesced braid bars (e.g. Bridge, 1993, his fig. 4). Following Smith and Smith (1980, their fig. 6) and Nanson and Knighton (1996), it can be concluded that it is the nature of the islands, rather than their size, which discriminates anastomosing rivers from braided rivers.

2.3. Floodplain geomorphology

The long recognized genetic association between rivers and their floodplains led Nanson and Croke (1992) to a classification of floodplains rather than rivers. It seems reasonable to assume that anastomosing rivers, if genetically, hydraulically and sedimentologically distinct, are characterized by a different floodplain geomorphology too. Some authors, in discussing anastomosing river floodplain geomorphology, have also paid attention to the stabilizing effect of vegetation.

Smith (1976) suggested the stabilizing effect of vegetation is a major factor in the development of anastomosing river morphology. Rust (1981), however, described an anastomosing river in an arid environment on a scarcely vegetated floodplain and concluded that the role of vegetation is less important on arid floodplains. It is obvious that vegetation, being strongly climatically dependent, cannot serve as a universal characteristic of anastomosing rivers.

The morphology of alluvial islands in an anastomosing reach of the Solimões River (Amazon Basin) was described by Sternberg (1959, p. 400) and Baker (1978, p. 225) as 'saucer-like' due to the bounding natural levees. Savat (1975, p. 168) described islands of his Kwilu-type rivers in the Zaire Basin likewise as: "mini alluvial plains: surrounded by levee deposits". In various papers, extensive wetlands (mainly comprising the islands) and narrow prominent natural levees (Fig. 2) were mentioned as characteristics of anastomosing river floodplains in humid climates (Smith and Smith, 1980; Smith and Putnam, 1980; Smith, 1983, 1986). Anastomosing systems in arid and semi-arid climates (Rust, 1981; Nanson et al., 1986; Schumann, 1989) lack these wetlands due to aridity, but the islands to some extent do have the saucer-like morphology that distinguishes them from braid bars, although levees often are less pronounced. In some anastomosing river systems, levees are absent or very subtle phenomena and islands are just near-level parts of the floodplain enclosed by multiple channel belts (Taylor, 1999).

Although the rarity or absence of meander scrolls and oxbow lakes on anastomosing river floodplains was considered to be a fundamental characteristic by some workers (Smith, 1983, his Table 2; Nanson and Croke, 1992), this is not generally agreed upon. Riley (1975, p. 3), outlining the differences between distributary and braided channels in eastern Australia, noted: "Cutoffs, point bars and meander scrolls can all be found in association with the individual distributaries". Later, these distributary channels were called anastomosing channels by Taylor and Woodyer (1978). They regarded the topography of the floodplain referred to by Riley, however, as relic.

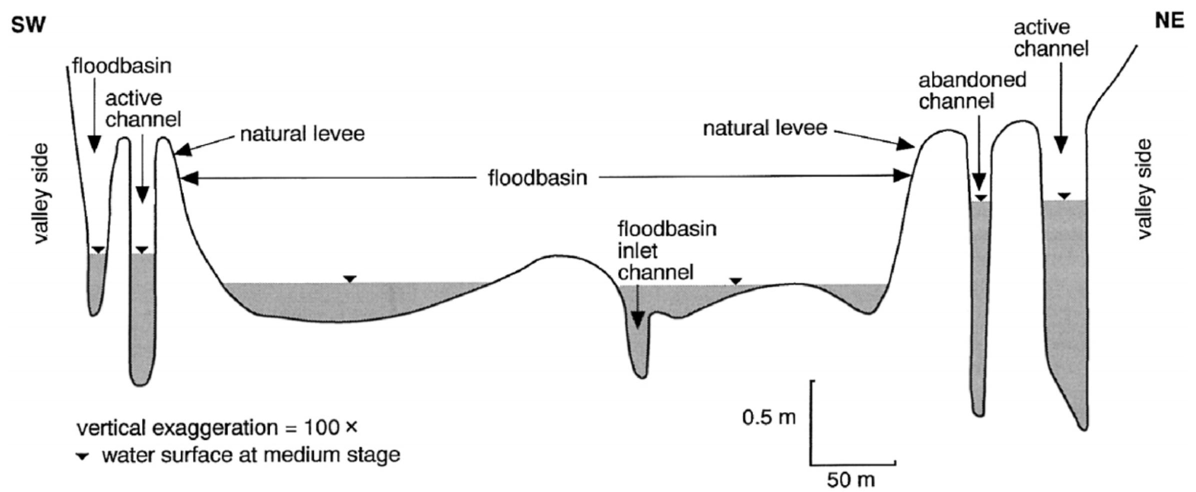


Fig. 2. Topographic profile across the floodplain of the anastomosing Alexandra River, Alberta, Canada (after Smith and Smith, 1980).

Brizga and Finlayson (1990) described a recent (1952) channel avulsion of the Thomson River in Australia, leading to coexistence of two meandering channels which both show point bars. The new channel has a narrow meander belt only. It is unclear whether anastomosis is a temporary situation in this case. Elsewhere in Australia, Bowler et al. (1978) documented a wide meander belt with scroll patterns for what they called 'anabranches' of the Darling River, which in turn was typified by a narrow meander belt. Nowadays, the anabranches transport floodwaters only. Schumm et al. (1996) described anastomosing channels of the Ovens and King Rivers in south-eastern Australia as becoming more sinuous with time. In the same region, Erskine (personal communication in Nanson and Knighton, 1996) also identified laterally migrating anastomosing channels of the Murray River. Outside Australia, Baker (1978) mentioned prominent scroll topography on anastomosing river floodplains of the Solimões River.

It can be concluded that, although meander belts with ridge-and-swale topography generally are not characteristic features of anastomosing river floodplains, they may be present. Consequently, it seems that meandering and anastomosing are not mutually exclusive characteristics of a river, which harmonizes with Schumm's (1968, 1985) idea to classify anastomosis as a higher order pattern consisting of multiple channels which can either be straight, meandering or braided. Most authors agree that floodbasins constitute a major element of the geomorphology of anastomosing river floodplains, including the islands between the anastomosing channels. In contrast, islands within braided channels typically have a convex-up morphology.

In this paper, the term 'floodbasin' stands for a flat, shallow, poorly drained floodplain depression bounded by natural levees of active or abandoned channels or other uplands (Fig. 2). Floodbasins may be very extensive and in wet climates they are typically swampy for most of the year. Therefore, the term 'backswamp' was used as a synonym, particularly in the Lower Mississippi Valley (e.g. Saucier, 1994, pp. 126–127). To stress the geomorphology of these areas, rather than the climatically dependent hydrological situation, the term floodbasin is preferred here. It is acknowledged, however, that not all fluvial systems do form pronounced levees, and hence in some cases 'floodbasins' may rather be near-level overbank areas.

2.4. Proposed definition and classification

In view of the considerations in the preceding sections, I propose the following definition of anastomosing rivers based on channel pattern and floodplain geomorphology: *an anastomosing river is composed of two or more interconnected channels that enclose floodbasins*. Below, I will elucidate the three basic points of the related classification of river types shown in Fig. 3.

Firstly, anastomosing rivers are classified as rivers having multiple coexistent channel belts, while braided rivers are regarded as rivers with a single channel belt, but multiple thalwegs. Although the term 'channel belt' originally referred to the zone in which a meandering channel has been active [more commonly termed 'meander belt' (e.g. Fisk, 1947)], here its meaning is widened to involve the zone of activity of a straight, meandering or braided channel, including bars, abandoned channel segments, crevasse splays and levees, and which is bounded laterally by floodbasins or the floodplain margin. Generally, islands in an anastomosing river are larger than islands or bars in a braided river, which genetically are in-channel features. Geomorphologically, saucer-shaped islands (floodbasins) characterize anastomosing rivers, while convex-up islands (bars) characterize braided rivers. Meandering and straight rivers are classified as rivers with both a single channel belt and a single thalweg, since the flow in their channel is not split by in-channel bars. To distinguish between rivers with single and multiple thalwegs, the braid-channel ratio (B) of Friend and Sinha (1993) is applied, which is defined as the sum of the mid-channel lengths of all the segments of primary channels in a reach divided by the mid-channel length of the widest channel through the reach. Here, a channel is taken to be braided if its braid-channel ratio is >1.5, although this value is quite arbitrary and scattered braids already occur in channels with braid-channel ratios between 1.0 and 1.5. The braid-channel ratio is preferable to the braiding parameter ($B.P.$) of Rust (1978), since the latter, being loosely defined as the number of braids per mean meander wave-length, requires identifica-

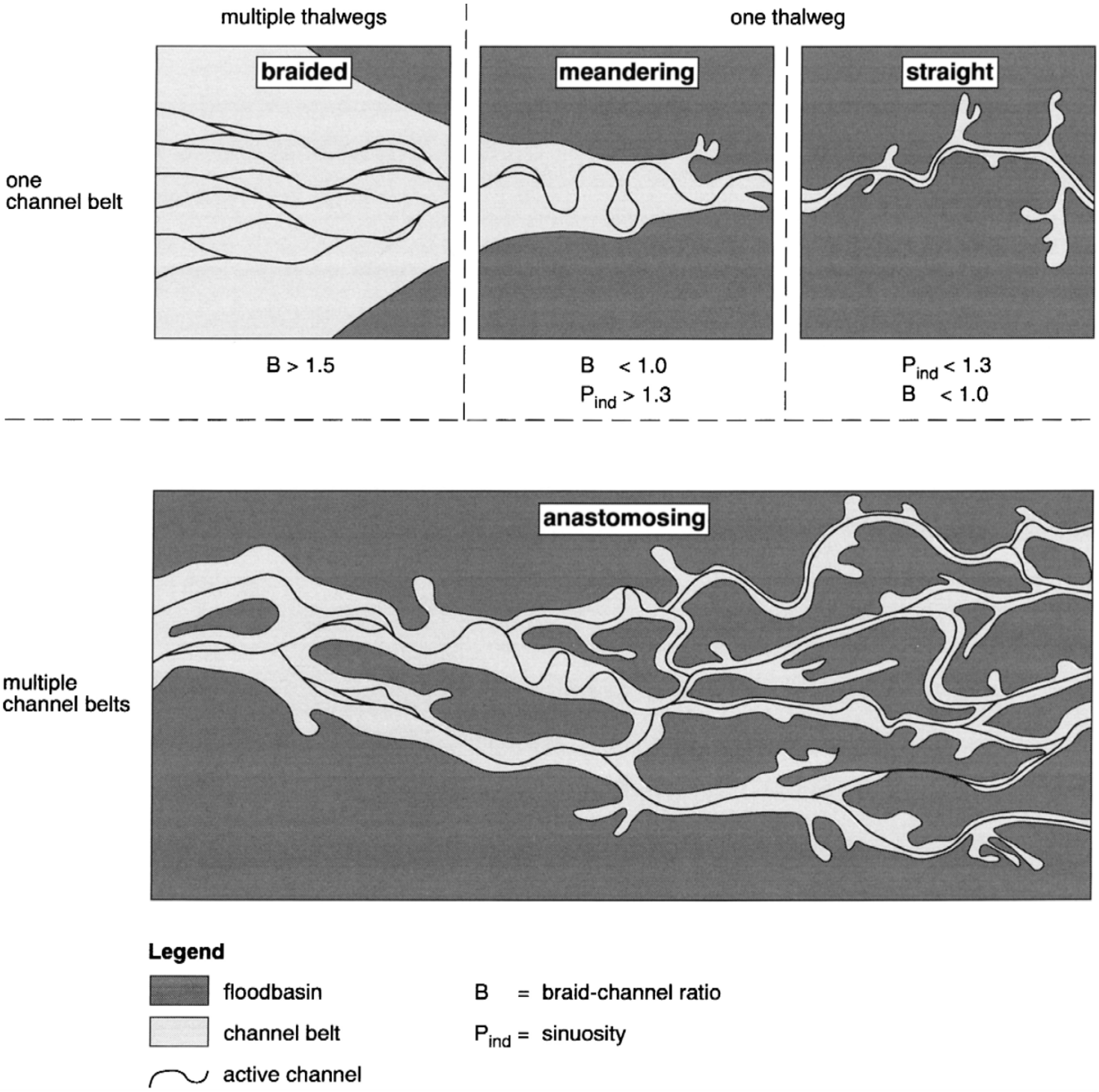


Fig. 3. Proposed classification of alluvial river types based on channel pattern and floodplain geomorphology. Anastomosing rivers (below) are classified as a composite form of which the individual channel belts may have braided, meandering or straight channels (above).

tion of meanders for rivers that may not show any tendency towards meandering.

Secondly, straight and meandering rivers are defined with respect to the channel belt. Straight in this sense does not necessarily mean literally straight, but it means that the course of the channel and the course of the axis of the channel belt are very similar, i.e. absence of lateral erosion and deposition. Meandering in this sense means that a reach of the channel is substantially longer than the corresponding reach of the channel belt. To describe these phenomena, Brice (1964) introduced the sinuosity index (P_{ind}), defined as the ratio of the channel length to the length of the meander-belt axis. A sinuosity index of 1.3 is proposed as a boundary value that separates straight from meandering channels. For a given channel reach, the sinuosity index will generally be lower than the sinuosity ($P =$ distance along the channel divided by straight line distance), for which 1.5 is usually accepted as a boundary value between meandering and straight (Leopold and Wolman, 1957; Rust, 1978).

Thirdly, anastomosing rivers are classified as a composite form of which the individual channel belts may have braided, meandering or straight channels. This is in accordance with the classification of Schumm (1968, 1985). An anastomosing river composed of multiple braided channel belts seems to be an exceptional form, with rare examples mentioned by Smith and Smith (1980, their Fig. 6) and Taylor (1999). Meandering channels are not common features of anastomosing rivers, but they may occur. Most anastomosing rivers consist of straight channels (e.g. Smith and Smith, 1980; Rust, 1981; Smith, 1983). However, there is no fundamental reason for an a priori exclusion of meandering and braided channels in anastomosing rivers by definition. For simplicity, in this classification straight, meandering and braided are presented as mutually exclusive properties of a channel belt. In fact, this is only correct for straight and meandering, being defined by sinuosity index only. In theory, a braided channel belt may at the same time also be straight or meandering. However, in this classification a channel belt with multiple thalwegs ($B > 1.5$) is simply classified as braided irrespective of its sinuosity index.

An important advantage of this classification is that it can be applied at the local scale of individual channel reaches, without regard to the rest of the system. Strictly speaking, when considering isolated reaches of a channel, the term anastomosing has no meaning. This is important especially when interpreting fluvial sediments, as exposure is often limited to individual channel deposits and rarely will the reconstruction of a multi-channel palaeoriver be possible (see also Section 4.5).

The classification is also meaningful with regard to the genesis and sedimentology of rivers. The hierarchical difference in the classification between braided, meandering, and straight rivers with single channel belts, on the one hand, and anastomosing rivers with multiple channel belts on the other hand, reflects fundamental differences in genesis between these two categories. Straight, meandering and braided rivers all basically result from in-channel processes such as lateral erosion and accretion or mid-channel bar formation. Anastomosing rivers result from extra-channel processes, namely floodplain formation by overbank deposition and avulsion, i.e., the partial diversion of flow from an existing channel onto the floodplain (see Section 3.2). The identification of floodbasins, which is inherent to the classification is genetically significant since these areas provide avulsion routes, and their state of preservation provides information on the lateral activity of the channels. In addition, their identification is sedimentologically significant, as they indicate major lateral differentiation in sedimentary facies from channel to floodbasin.

As will be illustrated in the next sections, anastomosing rivers can occur in various geological settings, including deltaic and coastal plains. Deltaic fluvial systems that are principally distributive may also be partly anastomosing, when radial distributaries are interconnected or have bypasses that rejoin downstream. It is hypothesized that such deltaic fluvial systems are not fundamentally different from inland anastomosing rivers in forms, processes and sediments (see also Makaske, 1998). Another category of radial multi-channel systems that may also be partly anastomosing includes the low-sinuosity meandering alluvial fans described by Stanistreet and McCarthy (1993). However, most alluvial fans are characterized by non-anastomosing, strictly radial patterns.

The focus of this paper is on anastomosing rivers and therefore only three basic (single channel-belt) river types are discerned. This is a simplification, as nowadays more river types are recognized in a continuum from straight (as defined above) to braided. One of these is the wandering river, which is mentioned here because the term anastomosing was frequently applied to it (e.g. Mollard, 1973; Church, 1983, p. 180). Wandering rivers, as described by Church (1983) and Carson (1984b), occupy an intermediate position between meandering and braided (e.g. Nanson and Croke, 1992; Hickin, 1993). Because of the presence of relatively stable vegetated islands in these rivers, they resemble anastomosing rivers in pattern. However, in well-documented wandering rivers multiple channels and thalwegs exist within one channel belt occupying a narrow floodplain confined by valley walls. If floodplains were wider, multiple wandering river channel belts could in principle form an anastomosing complex.

It must be stressed that the proposed classification applies to alluvial rivers only. Non-alluvial rivers may to some extent resemble the classified alluvial rivers; for example, the steep-gradient ($S_{ch} \approx 12$ m/km) 'anastomosing' streams described by Miller (1991). However, these degrading streams lack lateral floodbasins and, moreover, they are fundamentally different in process since avulsion sites are determined by resistant bedrock strata.

Nanson and Knighton (1996) recently defined *anabranching* rivers as: "systems of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull". They distinguished six types of anabranching rivers on the basis of stream power, sediment texture and river morphology. These types included several types of wandering rivers as well as anastomosing rivers. The anastomosing rivers as defined in this paper, comprise their types 1, 2 and 3 anabranching rivers. These are: cohesive sediment anabranching rivers (type 1), sand-dominated, island-forming anabranching rivers (type 2), and mixed-load laterally active anabranching rivers (type 3). Despite differences in sediment and channel morphology, all three of these river types have floodbasins on their islands.

A limitation of the present classification is the stage-dependency of the definition of braided and anastomosing rivers. At high stages braided rivers with submerged bars may seem single-thread channels, while at low stages anastomosing rivers may carry water in a single main channel only, thereby appearing as single-channel rivers. For proper classification, rivers should be observed at various stages.

3. The origin of anastomosing rivers

3.1. Introduction

Anastomosing rivers occur in a variety of environments. Climatic conditions vary from subarctic or temperate to tropical humid or arid. Geological settings include montane, foreland and intracratonic basins as well as coastal environments. The spatial scales of anastomosing rivers also vary widely (Table 2). However, it cannot be concluded that the formation of anastomosing rivers is completely independent of climate and geological setting.

The geomorphological processes in anastomosing rivers are of two kinds: (1) the processes creating the pattern of multiple channel belts, i.e. the processes associated with avulsion, and (2) the processes determining the morphology of the individual channel belts of the system. In many different ways, climate and geology are important external controls of these processes.

3.2. Avulsion

Allen (1965, p. 119) defined avulsion as: "the sudden abandonment of a part or the whole of a meander belt by a stream for some new course at a lower level on the floodplain". Sometimes this is referred to as first-order avulsion, with second and third-order avulsion relating to reoccupation of old channels and initiation of new braids within a braided channel, respectively (e.g. Nanson and Knighton, 1996, p. 219). In this paper I will use the term avulsion in the sense of Allen (1965), i.e., relating to the process of formation of a new channel belt. However, Allen unjustly restricted avulsion to meandering rivers only. It is also recognized now that 'sudden abandonment' of the existing channel belt not necessarily follows the formation of a new channel belt. Therefore, avulsion is better defined as: the diversion of flow from an existing channel onto the floodplain, eventually resulting in a new channel belt. As a product of avulsion, anastomosing rivers essentially form in two ways: (1) by formation of bypasses, while bypassed older channel-belt segments remain active for some period; and (2) by splitting of the diverted avulsive flow, leading to contemporaneous scour of multiple channels on the floodplain. The latter type of anastomosis may temporarily exist as a by-product of an avulsion within a larger-scale anastomosing system that was formed by successive avulsive formation of new bypasses. A hierarchy may thus exist.

Avulsion can take place in a variety of alluvial environments. It has been reported from braided rivers on alluvial fans (Gole and Chitale, 1966; Knight, 1975; Wells and Dorr, 1987; Gohain and Parkash, 1990), braided river floodplains (Coleman, 1969; Nordseth, 1973; Carson, 1984b; Bristow, 1999; Ethridge et al., 1999), meandering river floodplains (Fisk, 1944; Russell, 1954; Mike, 1975; Brizga and Finlayson, 1990; Neller et al., 1992; Mack and Leeder, 1998; Smith et al., 1998), and deltaic plains (Fisk, 1944; Kruit, 1955; Elliot, 1974; Berendsen, 1982; Törnqvist, 1994; Van Gelder et al., 1994; Makaske, 1998).

Subsequent to avulsions, old channels may be abandoned at variable rates. Extremely rapid was the shift to a new course of the Yellow River in 1855, which came about in 1 day (Qian, 1990). Törnqvist (1993b, pp. 155–157) described examples of relatively rapid (period of coexistence of old and new channel < 200 years) as well as more gradual (period of coexistence 500–1000 years) avulsion in the Rhine–Meuse delta in the Netherlands. It seems that especially in anastomosing rivers, the abandonment of old channels may be a very slow process and in some cases new avulsion channels obviously remain as secondary channels and never take over the entire discharge of the old channels, Eventually, these new secondary channels may be abandoned earlier than the older trunk channels. Formation and subsequent abandonment of such a secondary channel may be referred to as a 'failed' avulsion (Makaske, 1998, pp. 220–224; Guccione et al., 1999). In principle, frequent avulsions and/or slow abandonment of old channels lead to continuing coexistence of younger deepening channels and old vertically infilling channels, composing an anastomosing system.

The role of avulsion in the formation of anastomosing systems is recognized by many investigators (Riley and Taylor, 1978; Woodyer et al., 1979; McIntosh, 1983; Smith, 1983; Jacobberger, 1987; Smith et al., 1989, 1997; Schumann, 1989; McCarthy et al., 1992). Here, the following questions are addressed: (a) what kind of floodplain facilitates avulsions, (b) what initiates the avulsion process, and (c) what is the evolution of the avulsion channel after initiation of the process?

Bridge and Leeder (1979) stated that: "Avulsion is initiated if floodwaters travelling from an alluvial ridge to the floodbasin, through crevasses or low parts of the levees, have a gradient advantage over the main channel". Thus, the avulsion process is caused by the formation of alluvial ridges, as the deposition rate close to the channel is generally much higher than it is in the adjacent floodbasin. Mackey and Bridge (1995) expressed this relationship mathematically as follows:

$$r_z = a\mathrm{e}^{-b(z_c/z_m)}$$

in which: r_z = deposition rate (m/year), at distance z (m) from the edge of the channel belt; a = maximum net deposition rate (m/year) at the edge of the channel belt; z_c/z_m = dimensionless distance from the channel belt (–); b = coefficient that describes the rapidity at which the rate of deposition decreases with distance from the channel belt.

Mackey and Bridge (1995) argued that realistic values of b range from 0.35 to 1.4. Considerably higher values of b ranging between 3 and 7 were calculated by Törnqvist et al. (1996) based on borehole data from the Rhine–Meuse and Mississippi deltaic plains covering long (1500 years) time spans. Similar values of b were obtained by Törnqvist et al. (1996) from single-flood data from the Rhine–Meuse delta. These high values of b suggest a relatively rapid formation of natural levees. Higher compaction rates of silty, clayey and peaty floodbasin deposits with respect to gravelly and sandy channel-belt deposits, further enhance the formation of alluvial ridges. Based on theoretical considerations, Bridge and Leeder (1979) suggested that avulsion frequency increases with aggradation rate. This was confirmed by field data on the Holocene development of distributaries in the Rhine–Meuse delta, showing that the avulsion frequency was highest in the period of high sedimentation rate due to rapid sea-level rise. The number of avulsions decreased when the rate of sea-level rise decreased and the aggradation rates slowed down (Törnqvist, 1994). An example of exceptionally high avulsion frequency (avulsion every twelfth year on average) associated with very rapid vertical aggradation was described for the modern Yellow River delta (Van Gelder et al., 1994). Experimental evidence for a rise of avulsion frequency with increasing sedimentation rate was given by Bryant et al. (1995). In case of alluvial fans and deltas, local high sedimentation rates near the fixed entry point obviously favour the avulsion process and cause an avulsion node, i.e., a small area where avulsion occurs much more frequently than elsewhere. The resulting semi-circular fan or delta with a convex-up cross profile is highly conductive to random avulsions, i.e., avulsions not occurring at the avulsion node but scattered over the floodplain. This is well documented for the Kosi River alluvial fan in northern India (Gole and Chitale, 1966; Wells and Dorr, 1987; Gohain and Parkash, 1990; Mackey and Bridge, 1995, pp. 20–23).

Another boundary condition that controls the avulsion process is the overall gradient of the floodplain. At a given aggradation rate, favourable conditions for avulsion (i.e. gradient advantage across the natural levee compared to the main channel) are attained more easily on a low-gradient floodplain than on a high-gradient floodplain because of the low channel gradients involved. The overall floodplain gradient can be strongly influenced by tectonics. Tilting of the floodplain can give rise to frequent avulsion in a preferential direction. Alexander and Leeder (1987) called this ‘topographically triggered avulsion’. This effect was also quantified in simulation models for alluvial stratigraphy (Bridge and Leeder, 1979; Bridge and Mackey, 1993; Mackey and Bridge, 1995). Field examples are documented for the Brahmaputra River (Coleman, 1969), the rivers on the Hungarian Plain (Mike, 1975) and rivers in the upper Amazon foreland basins (Dumont, 1994). Tricart (1965) and Gallais (1967) suggested rapid local subsidence as a controlling mechanism for a sequence of eastward avulsions of the Bani and Niger Rivers (central Mali). Makaske (1998, pp. 168–169) elaborated on the relationship between the half-graben tectonic framework and the avulsion history of this region.

Once the conditions on the floodplain are favourable for avulsion, a trigger is needed to initiate the process. Jones and Schumm (1999) recently published a useful overview of avulsion triggers and also introduced the concept of the avulsion threshold, i.e., a state of extreme channel instability resulting in avulsion. As explained above, aggradation may move a channel towards the avulsion threshold. The closer a channel is to the avulsion threshold, the smaller the event needed to trigger the avulsion. Triggers may determine the time as well as the location of avulsion. A large flood usually determines the time of an avulsion (Brizga and Finlayson, 1990; Mack and Leeder, 1998). Therefore, Knighton and Nanson (1993) argued that a flow regime characterized by concentrated floods of relatively high magnitude is conductive to anastomosis. Another possible trigger is a sudden tectonic event resulting in bank collapse or breaching (Alexander and Leeder, 1987). More common triggers are obstructions, blocking discharge in the main channel and forcing the water to seek a new course, starting as a crevasse through the natural levee (Smith, 1983). Channel obstructions mentioned in the literature include: beaver dams (Rutten, 1967), log jams (Smith, 1983; Harwood and Brown, 1993), and ice jams (King and Martini, 1984, Ethridge et al., 1999) in cold to temperate climates, and dunes (McIntosh, 1983; Jacobberger, 1988b; Makaske, 1998, pp. 163–164) in arid climates. Examples of weak spots in the natural levee where crevasses preferentially form, are beaver (Smith, 1983) or hippopotamus trails (McCarthy et al., 1992). Not all crevasses develop into mature avulsion channels. In fact, the majority will become plugged up again (Smith, 1983). Slingerland and Smith (1998) presented a quantitative conceptual model showing that whether a crevasse will heal or lead to an avulsion depends upon sediment grain size, the initial depth of the crevasse and the ratio of crevasse, to main channel bed slopes.

Although the usual perception is that avulsions are basically driven by development of floodplain relief through channel-belt aggradation, there is evidence for an additional mechanism. In studies on arid and semi-arid anastomosing river floodplains, the loss of channel-flow capacity caused by in-channel fluvial deposition has been suggested as a driving mechanism of avulsions. On the Cooper Creek and Upper Darling River floodplains, flood regimes are typically flashy, and bankfull discharge is exceeded far less than once every year (Riley and Taylor, 1978; Taylor and Woodyer, 1978; Woodyer et al., 1979; Rust, 1981; Schumann, 1989; Gibling et al., 1998). Due to this, floodplain sedimentation rates are relatively low (Table 2), and most sediment load is deposited within the channels during base-flow conditions. The in-channel deposits may be fine-grained and frequently have a bench morphology (Riley and Taylor, 1978; Taylor and Woodyer, 1978; Woodyer et al., 1979; Schumann, 1989; Gibling et al., 1998). Consequently, the channel looses capacity to accommodate the next flood and becomes liable to avulsion. Loss of channel-flow capacity as a driving mechanism of avulsions may not be exclusively tied to slowly aggrading floodplains in arid climates. Makaske (1998, pp. 93–96) suggested a similar mechanism for the more rapidly aggrading floodplain of the anastomosing upper Columbia River in temperate humid western Canada (Table 2), where measurements and calculations of sediment transport indicate substantial storage of coarse sediment load on the beds of laterally stable channels. If bed aggradation locally outpaces levee aggradation, flow is forced out of the channels onto the floodplain where new channels are cut. This avulsion-mechanism need not be in conflict with the notion that avulsions are driven by the evolution of floodplain relief, but rather complements it. Another avulsion-mechanism was presented by Schumm et al. (1996), who explained avulsions of the anastomosing Ovens and King Rivers as a response to loss of hydraulic efficiency as channels became more sinuous with time.

In any case, the chances for avulsion increase as aggradation continues, but where and when will avulsion ultimately take place? During floods, the outer bends seem to be the most favourable spots for avulsion. Smith et al. (1998) mention three reasons for this: (1) water-surface superelevation and higher velocities in the outer bend lead to higher erosive power at potential avulsion sites; (2) inertia of flow in the outer bend directs overbank flow at a high angle away from the channel flow towards the floodbasins; and (3) levees in the outer bend tend to be narrow due to lateral erosion and have a steep floodbasinward slope. Additionally, Smith et al. (1998) showed with a numerical flow model how a chute cut-off could have triggered the 1870s avulsion of the Saskatchewan River by raising the water-surface elevation in the cut-off bend. Nevertheless, predicting the exact time of avulsion is impossible, due to the random nature of extreme floods and the various triggers. Bridge and Leeder (1979) therefore argued that it should be treated as a stochastic process.

During the process of avulsion as described by Smith et al. (1989) for the lower Saskatchewan River, anastomosis developed within the avulsion belt (i.e., the zone of the floodplain affected by an avulsion), resulting from contemporaneous scour of multiple channels. In their model, the avulsion belt starts as a small lobate crevasse splay that gradually develops into a large elongate crevasse splay complex with a highly irregular planform. On the incipient crevasse splay unstable multi-channel patterns exist. Along with splay progradation into the wetlands, the channels on the older part of the splay complex, start building natural levees and become more stable. During progradation, channelized flow may bifurcate at channel-mouth bars, resulting in the formation of separate splay lobes with their own channels, prograding into the wetlands (Fig. 4). Often the developing channels rejoin further downstream surrounding small floodbasin areas (Smith et al., 1989, pp. 7–8; Smith and Pérez-Arlucea, 1994, their fig. 4). This type of anastomosis is considered a stage in the avulsion cycle and therefore is relatively short-lived. The final stage is a single channel, deeply scoured through the inactive crevasse splay complex and taking over all discharge from the temporary multi-channel system. A similar avulsion-cycle was described by Van Gelder et al. (1994) for the Yellow River delta.

The above-described avulsion process, which involves crevasse splay formation during very high sediment supply to the floodbasin (see also Ethridge et al., 1999), is valid for rapidly aggrading systems only. Alternatively, in slowly aggrading systems, avulsion is a predominantly erosive process. Rust (1981), for example, observed the absence of crevasse splays and the presence of only poorly developed, discontinuous natural levees in the slowly aggrading Cooper Creek anastomosing system. He therefore argued that avulsion here takes place without prior crevasse splay formation. Schumann (1989) described the formation of avulsion channels in the arid Red Creek system after only minor crevasse splay formation. In contrast to the process described by Smith et al. (1989), channelization of flow in the Red Creek system starts downstream, where the avulsion flow rejoins the main channel, and gradually travels upstream to the point where the avulsion was initiated. Gibling et al. (1998) and McCarthy et al. (1992) proposed a similar mechanism for the formation of avulsion channels at Cooper Creek and in the Okavango Delta, respectively. An exceptional feature in the Okavango Delta, is that water from the main channel percolates to the backswamps through permeable banks that are composed solely of vegeta-

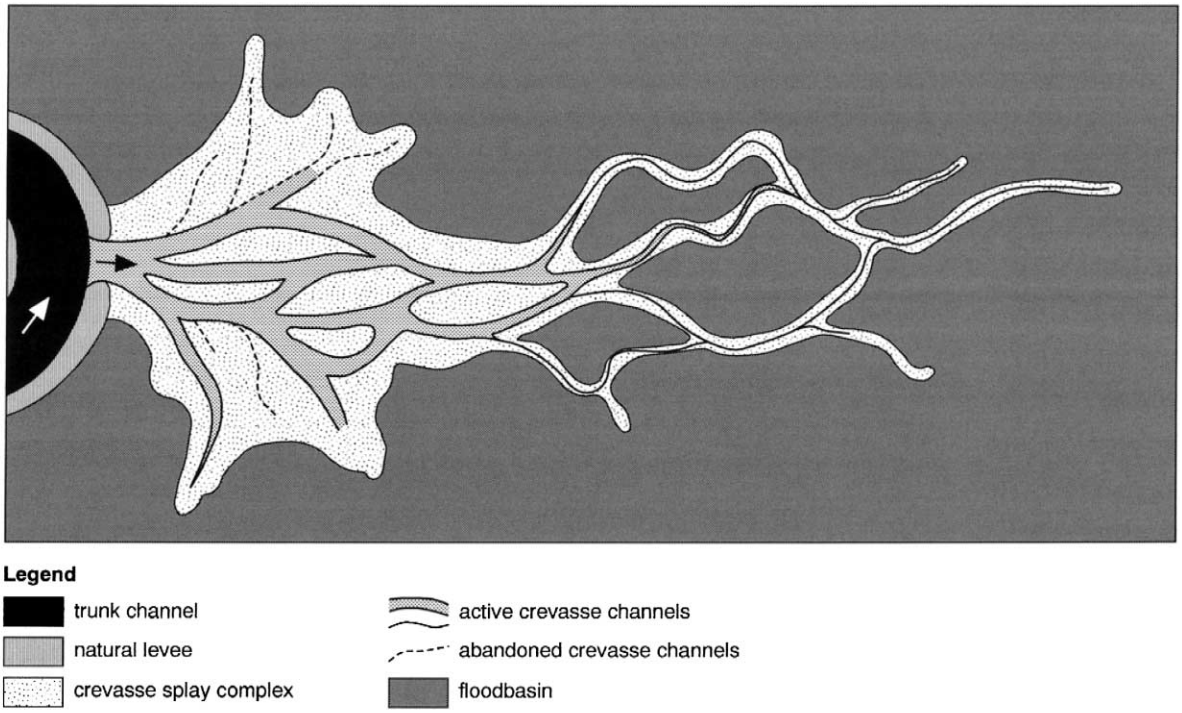


Fig. 4. Anastomosing channel pattern within a developing avulsion belt. From the initial massive crevasse splay complex shown on the left, narrow lobes with channels prograded to the right, eventually rejoining and enclosing parts of the floodbasin. The trunk channel on the left may be part of a larger-scale anastomosing system not shown here (modified from Makaske, 1998).

tion, as well as spilling over the banks. A slightly different mode of channel formation was described by Taylor (1999) for the anastomosing Fitzroy River. In this system, high-magnitude overbank flows are able to scour new channels on the floodplain that initially lack upstream and downstream connection with existing channels, but that gradually may extend to become part of the anastomosing system. Aslan and Blum (1999) inferred two different styles of avulsion for Texas Gulf Coastal Plain rivers in response to different floodplain aggradation rates. During periods of low aggradation, avulsion took place by reoccupation of abandoned channels on the floodplain, with very little avulsion-related sediment deposition. In contrast, during periods of high aggradation, avulsion came about by diversion into floodbasins leading to metres-thick successions of avulsion deposits.

Channel chronologies for some anastomosing systems with good radiocarbon control, the upper Columbia and lower Saskatchewan Rivers, prove avulsion to be frequent. Nine major avulsions since 4000 and 5400 BP, respectively, could be recognized in floodplain-wide cross-sections of these systems (Makaske, 1998, pp. 70–76; Morozova and Smith, 1999). Both systems are characterized by high floodplain aggradation rates (Table 2). The scarce field evidence suggests that among different anastomosing rivers, avulsion frequencies decrease with decreasing floodplain aggradation rates, in accordance with results of simulation studies (Bryant et al., 1995) and studies of fluvial deltaic sequences (Törnqvist, 1994; Stouthamer and Berendsen, 1997). In the slower aggrading upper Inland Niger delta (Table 2), for example, only three major avulsions occurred during the Holocene (Makaske, 1998, pp. 159–170). Also in the extremely slowly aggrading anastomosing systems of the Channel Country [including Cooper Creek (Table 2)] avulsion seems to be a rare process. Channel chronologies are absent for this arid system, due to poor conditions for radiometric dating, but air photos show no signs of avulsions over an area of

8000 km^2 since the 1940s. The trees lining the anastomosing channels are hundreds of years old, indicating stability over this period (G.C. Nanson, personal communication, 2000).

Anastomosing rivers systems with a low avulsion frequency, seem to maintain a multi-channel state by very slow abandonment of old channel segments after avulsive formation of bypasses. Over long interavulsion periods, these anastomosing rivers are virtually static multi-channel systems. Little is known about the factors determining the rate of channel abandonment after avulsive switching. Given the characteristics of the Channel Country anastomosing systems (Gibling et al., 1998), where avulsion frequency is believed to be very low, the following factors are considered important: (1) a low sediment load causing slow siltation of channels; (2) tough, strongly consolidated floodplain muds in combination with low stream power, allowing only slow enlargement of channel-flow capacity of new channels by bed scour and bank erosion; (3) little gradient advantage of avulsion channels over older channels on the low-gradient floodplain due to poor development of alluvial ridges; and (4) limited influence of vegetation due to aridity. The latter contrasts with plugging of old channels by woody debris jams and vegetation succession causing organic channel-fills in temperate humid systems.

In summary, frequent avulsion and/or slow abandonment of old channels leads to continuing existence of contemporaneously active channels on the floodplain. During the avulsion process, splitting and rejoining of the diverted flow may also cause temporary anastomosis within the avulsion belt. Frequent avulsion is most importantly caused by: (1) rapid channel-belt aggradation; (2) rapid in-channel deposition leading to shallowing; and (3) frequent occurrence of avulsion triggers. Common triggers are hydrological floods and obstructions temporarily reducing channel-flow capacity. Slow abandonment of old channel segments is expected to be mainly determined by: (1) a low sediment load; (2) tough, strongly consolidated floodplain muds in combination with low stream power of newly created channels; (3) little gradient advantage of avulsion channels over older channels; and (4) limited influence of vegetation. In general, most factors causing frequent avulsion and slow abandonment of old channels are linked to a low floodplain gradient, which therefore is a major underlying cause of anastomosis. The effect of aggradation, however, is ambiguous, since it obviously favours frequent avulsion, while to some extent it also favours the rapid abandonment of old channels.

3.3. Lateral channel stability

The lateral stability of the individual anastomosing channels has been pointed out in many studies (e.g. Smith, 1976, 1983, 1986; Smith and Smith, 1980; Rust, 1981; Nanson et al., 1986), so there appears to be a bias towards straight channels in anastomosing rivers. What is the reason for this?

Lateral stability of river channels is generally described as a function of slope, discharge and sediment composition of the banks. A basis for this idea was provided by the classic paper of Leopold and Wolman (1957). Plotting channel slope against bankfull discharge, they found that braided and meandering channels could be separated by the line:

$$S = 0.012\, Q_{bf}^{-0.44}$$

in which: S = channel gradient (–); Q_{bf} = bankfull discharge (m^3/s).

Straight channels were also plotted but were not discriminated by the above relationship in their diagram (Fig. 5). Schumm and Khan (1972) observed a straight–meandering–braided sequence of channel patterns in a series of experiments with increasing valley gradient at constant discharge (Fig. 6). In the same series of flume experiments, they showed that an increase in suspended sediment load has a stabilizing effect on the river banks. Later, however, it appeared that the duration of their experiments was too short to reach equilibrium channel patterns (Carson, 1984a, p. 331).

Discharge and slope can be combined into the single parameter of stream power. Stream power is often used as a tool to investigate the lateral stability of river channels (e.g. Chang, 1979; Ferguson, 1981; Richards, 1982; Keller and Brookes, 1984; Brown, 1987; Nanson and Croke, 1992; Van den Berg, 1995; Lecce, 1997; Makaske, 1998). One can distinguish between gross stream power and specific stream power. Gross stream power is defined as the rate at

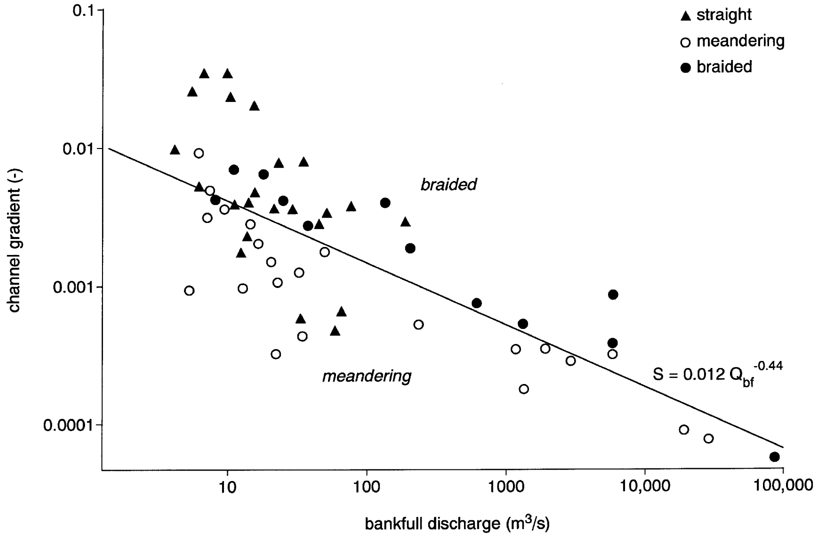


Fig. 5. Values of slope and bankfull discharge for various natural channels and a line separating fields of braided and meandering channels (after Knighton, 1984; modified from Leopold and Wolman, 1957).

which potential energy of water flowing downhill is supplied to a unit wet channel length:

$\Omega = \gamma g Q S$

in which: Ω = gross stream power (W/m); γ = density of water (kg/m^3); g = acceleration of gravity (m/s^2); Q = discharge (m^3/s); S = channel gradient (–). Specific stream power (ω) is gross stream power divided by channel width (w).

Ferguson (1981), working with data from 95 British rivers, concluded that inactive straight or sinuous channels tend to have low specific stream power (1–60 W/m^2), while actively shifting low-sinuosity channels have high stream power (> 100 W/m^2). Actively meandering channels have intermediate stream power values (5–350 W/m^2). These ranges of specific stream power, however, show wide overlaps.

Although certain ranges of slope–discharge combinations or stream power seem to be associated with certain channel patterns, it has been pointed out by various workers that these ranges characterize rather

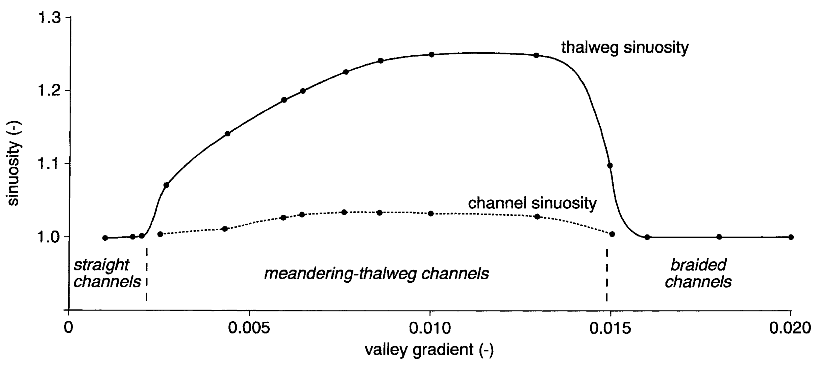


Fig. 6. Relation between the slope of the surface on which a channel was formed (valley slope) and thalweg sinuosity (after Schumm and Khan, 1972).

than predict those channel patterns (Carson, 1984a; Ferguson, 1987; Van den Berg, 1995). This is partly due to the use of bankfull discharge and channel slope, which are dependent on channel pattern. Moreover, the channel width, necessary to calculate specific stream power, is dependent on the channel morphology.

Most important, however, is that stream power represents a useful measure of the energy available to modify the channel only if it is related to the sediment to be moved (e.g. Schumm and Khan, 1972; Carson, 1984a; Ferguson, 1987; Van den Berg, 1995). Excess stream power above the threshold for sediment entrainment is believed to relate to channel behaviour (Carson, 1984a). Therefore, Nanson and Croke (1992) classified river floodplains on the basis of specific stream power in the channels and the texture of the sediment on the floodplain. They described anastomosing river floodplains as having gravel and sand in channels with a specific stream power <10 W/m^2 and abundant silt and clay on the floodplains. These floodplains were classified as low-energy cohesive floodplains.

Stream power considerations can be applied to channel reaches, but not to river systems with multiple channel belts. Knighton and Nanson (1993) plotted bankfull discharge against channel slope (as in Fig. 5) for anastomosing, braided and meandering rivers. In their diagram, most anastomosing rivers plot within a zone below braided and meandering rivers, indicating low stream power. However, they treated the anastomosing rivers as single hydraulic entities. For explaining channel processes, individual channel reaches of the anastomosing network should be considered because each channel adapts to its discharge independently of the other channels of the system. Distribution of discharge over various channels also means reduction of stream power. The resulting relatively low stream power per channel partly explains why channels in anastomosing systems tend to be quite stable laterally (e.g. Harwood and Brown, 1993, p. 747).

On low-gradient floodplains where mean stream power is low, insufficient energy is available to enlarge channels, which therefore usually have little capacity to accommodate flood flows. Poor adjustment to flood flows for young channels in anastomosing networks results in slow abandonment of older channels, since they necessarily support a part of the peak discharge of the system. For the single-channel Blue River in Wisconsin, Lecce (1997) reported downstream decrease in gradient, channel capacity and mean stream power, resulting in an increase in magnitude and frequency of overbank flooding. Knighton (1987) stated that: “Alluvial rivers with erodible boundaries flow in self-formed channels which, when subject to relatively uniform governing conditions, are expected to show a consistency of form, or average geometry, adjusted to transmit the imposed water and sediment discharges”. One can seriously doubt whether this is true for anastomosing rivers. Knighton and Nanson (1993) regard the formation of anabranches as a response to the inability of the main channels to cope with high magnitude discharges, because “the resistivity of the banks constrains the size of the bankfull cross-sectional area”. Some humid climate anastomosing systems show prolonged annual flooding. For example, a mean of 45 days for the Columbia (Locking, 1983, p. 35), 50 days for the Magdalena (Smith, 1986) and even 100 days for the Solimões River (Mertes, 1994) floodplains were recorded. In semi-arid south-east Australia, Rutherfurd (1994) described anastomosing reaches of the Murray River, where spilling overbank occurs more frequently than in the reaches which have a single-channel morphology. Other semi-arid and arid climate anastomosing rivers experience significant long-term in-channel accretion and therefore seem to be unable to transmit imposed sediment load. (Riley and Taylor, 1978; Taylor and Woodyer, 1978; Woodyer et al., 1979; Rust, 1981; Schumann, 1989; Gibling et al., 1998). Sedimentary structures indicate that these in-channel deposits suffer virtually no erosion during subsequent floods (e.g. Riley and Taylor, 1978, p. 100). In the upper Columbia River a large fraction of the coarse bed material supplied from upstream is deposited in the anastomosing reach (Locking, 1983; Makaske, 1998). A part of this material may be trapped in large crevasse splays. Nevertheless, calculations and measurements of sediment transport suggest that supply of bedload greatly exceeds transport capacity within the anastomosing reach (Makaske, 1998, his Table 3.10).

When considering the stable channel morphology of anastomosing systems, time is an often neglected factor. Formation of wide alluvial ridges by active meandering of channels simply needs time. If channels are subject to frequent avulsive switching, for instance due to rapid channel-belt aggradation, then meanders may not fully develop because time of channel-belt occupation is too short, although average hydraulic conditions may favour slow lateral erosion and deposition. This means that, given constant rates of lateral migration, young channels seem laterally more stable than old channels. This probably played a role in the longitudinal facies architectural change of a palaeochannel described by Törnqvist et al. (1993). They found evidence for rapid downstream decrease in lateral migration of a subrecent channel, together with a downstream decreasing period of activity. Smith et al. (1989) suggested that under rapid aggradation, avulsions interrupt evolution of wide laterally accreted alluvial ridges in the anastomosing lower Saskatchewan River. Likewise, Kolb (1963) and Saucier (1994, pp. 123–124) explained differences in size of Holocene Mississippi River meander belts by differences in time of occupation. Thus, in some cases apparent lateral stability of anastomosing channels may be caused by relatively short periods of activity due to frequent avulsion.

Climatic influence on lateral channel stability occurs through the role of vegetation or duricrusts. In humid climates, vegetation and organic deposits have a stabilizing effect on river banks (e.g. Smith, 1976; Hickin, 1984; Harwood and Brown, 1993; Huang and Nanson, 1997). Cairncross et al. (1988) and Stanistreet et al. (1993) also described channel stabilization by extensive peat growth in a semi-arid anastomosing system. In arid environments, duricrust formation can be an important cause of channel confinement (Tricart, 1959; Friend et al., 1979; Gibling and Rust, 1990).

In summary, low stream power in combination with cohesive bank material explains the lateral stability of individual anastomosing channels. Low stream power is mainly caused by a low floodplain gradient that also favours avulsion (Section 3.2), although splitting of flow among different channels is an additional factor. The resistance against erosion of the banks is related to low stream power, since overbank deposition of clay takes place predominantly on low-gradient floodplains.

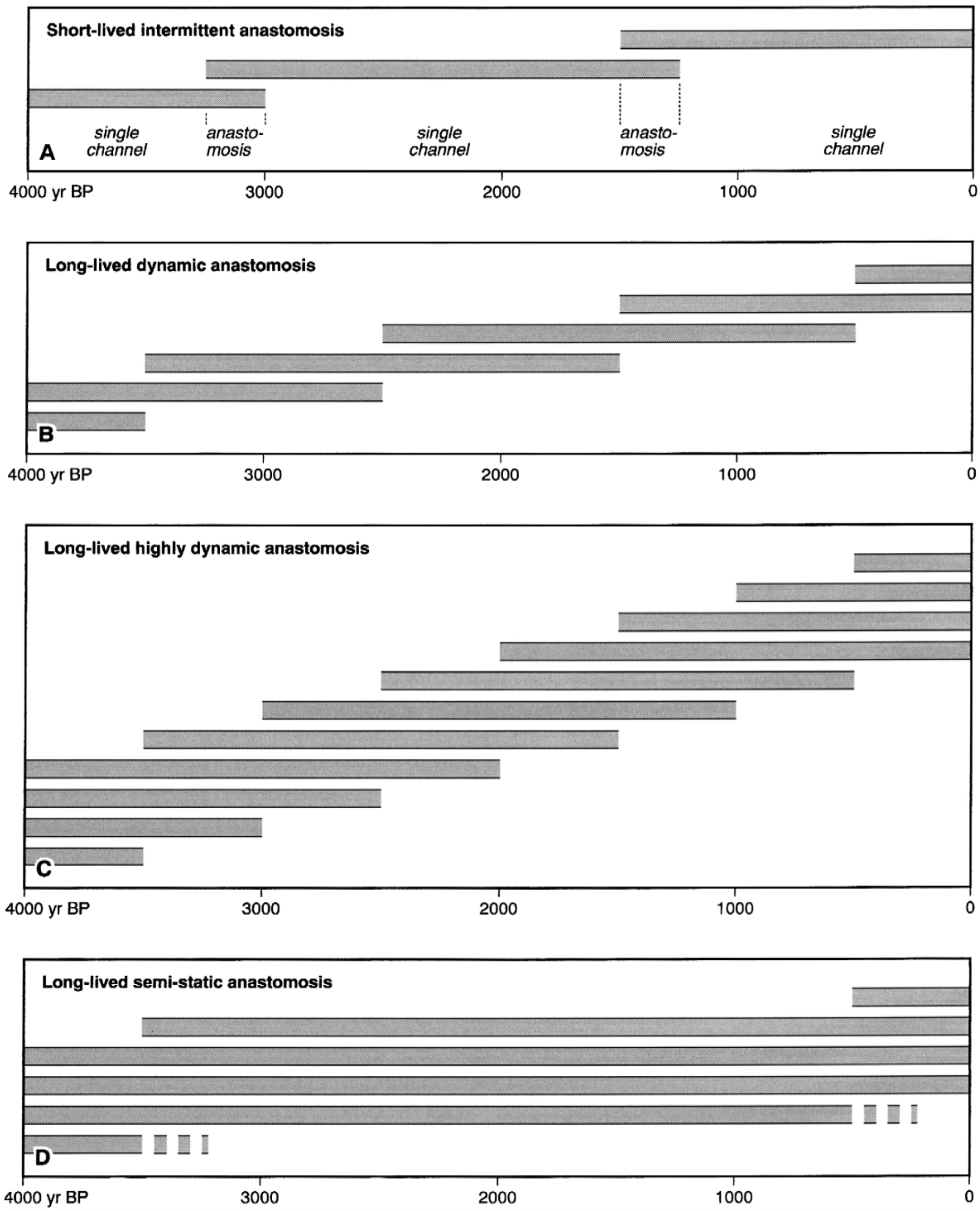
3.4. Climatic and base-level changes

Is anastomosis a state of transition, or is it an equilibrium form? In some cases, anastomosis is obviously transitional. For example, when anastomosis occurs within the avulsion belt as a result of splitting of the avulsive flow and contemporaneous scour of channels, as described for the lower Saskatchewan River by Smith et al. (1989). They considered a single channel belt as the normal state towards which the lower Saskatchewan River will return once the avulsion is completed. On a larger scale, rivers that usually have a single channel belt, may be anastomosed for relatively short periods during avulsive switching (Fig. 7A), when the new channel belt gradually takes over discharge from the older channel belt (e.g. Brizga and Finlayson, 1990). The question here is whether all rivers naturally strive for a single channel belt, and if so, which conditions prevent them from reaching that state, thereby causing long-lived anastomosis.

Some investigators regard anastomosis as an expression of instability induced by climatic change (Garner, 1959, 1967; Baker, 1978). Climatic change from aridity to humidity will subject channels of the drainage network to floods they cannot accommo-

Fig. 7. Diagrams showing theoretical channel chronologies for fluvial systems with anastomosis. Horizontal bars represent periods of activity of individual channels in a floodplain-wide cross section. Time scale only indicates order of magnitude. Note that anastomosing systems may range from short-lived to long-lived, and from very dynamic to semi-static, as a function of avulsion frequency and the time needed for total abandonment of older channels. (A) Fluvial system with a low avulsion frequency and for most of the time a single active channel belt. Brief periods of anastomosis occur during avulsive switching to a new channel belt. (B) Fluvial system in which relatively frequent avulsions and slow abandonment of older channels after avulsion lead to continuous anastomosis with two coexisting channels. (C) Fluvial system in which highly frequent avulsions and slow abandonment of older channels lead to continuous anastomosis with four coexisting channels. (D) Fluvial system in which infrequent avulsions and extremely slow abandonment of older channels lead to continuous anastomosis with four coexisting channels.

date. Bowler et al. (1978) believed that avulsion of the Darling River was associated with hydrological changes from late glacial arid to more humid Holocene conditions. In the arid Inland Niger Delta, degradation of the channel network due to in-channel fluvial and aeolian deposition is believed to have



been an important cause of avulsions at the onset of periods with increasing discharge (Gallais, 1967, p. 55; McIntosh, 1983; Makaske, 1998, pp. 170–171). Little is known about the response time of river systems to altered hydrological regimes.

An important indirect climatic influence is the rise in sea level in late Pleistocene and Holocene times. Such a rapid base-level rise can be considered as an instability imposed upon a fluvial system. Smith and Smith (1980) suggested: “In fluvial systems adjoining marine basins, rapid sea-level rise might provide a downstream control for upstream alluviation and possible development of channel anastomosis”. The idea of downstream control (Mackin, 1948) was first applied to anastomosing rivers by Smith (1973). Rapidly aggrading alluvial fans, deposited by tributaries entering an alluvial valley, provided local elevations of base level and caused upstream anastomosis. He stated that: “Under such conditions grade should decrease with aggradation” (Smith, 1973, p. 203). The combination of rapid aggradation and reduction of gradient favours avulsion frequency, while a low gradient also favours lateral channel stability. Rapid sea-level rise is considered a main factor for the coexistence of many laterally stable delta distributaries in the mid-Holocene Rhine–Meuse delta (Törnqvist et al., 1993; Törnqvist, 1993a, 1994; Makaske, 1998, p. 229). Evidence from other near-coastal areas is very limited. Another mechanism of base-level rise, important in some continental arid settings, is the formation of large dune fields blocking the course of a river. Jacobberger (1988a, p. 356) mentioned this as a prime cause for anastomosis in the Inland Niger Delta.

Tectonic or isostatic movements provide another cause for (relative) base-level rise. Local uplift of the riverbed reduces the river gradient upstream of the uplift, thereby inducing anastomosis. Evidence to support this mechanism is given by Burnett and Schumm (1983) and Ouchi (1985). On a larger scale, rapidly subsiding foreland basins are considered ideal settings for anastomosing river systems by Smith and Putnam (1980) and Smith (1986). Alternatively, Bakker et al. (1989) described Late Pleistocene anastomosing channel patterns in a subsiding, intramontane strike-slip basin, whereas McCarthy (1993) found intracratonic half grabens to be important settings for extensive modern anastomosing systems.

Whether a single channel belt is the norm for alluvial rivers, with anastomosis as an expression of instability remains open due to a poor hydraulic understanding of anastomosis. However, it is a fact that some anastomosing rivers are long-lived. Anastomosis of the upper Columbia River has persisted since nearly 3000 BP at least (Makaske, 1998, p. 75), while Morozova and Smith (1999, their Fig. 8) suggest coexistence of channels in the lower Saskatchewan River since approximately 4000 BP. Knighton and Nanson (1993, p. 622) even suppose that Cooper Creek has maintained as an anastomosing system for over 50,000 years; however, coexistence of channels over this period could not be proven. Nanson and Huang (1999) stated that anabranching (including anastomosing) rivers develop in order to maintain or enhance water and sediment throughput across extensive low-gradient floodplains. Supporting this statement with an analysis of basic hydraulic relationships, they considered anastomosing rivers as hydraulically efficient forms, more or less in equilibrium with imposed water and sediment discharges. Makaske (1998, p. 93) questioned the universal applicability of this concept and demonstrated the inefficiency of the anastomosing upper Columbia River and its inadequacy to transport the coarse bedload fraction.

If the concept of anastomosis as a state of disequilibrium is right, long-lived anastomosis points to continuous or repeated disturbance by allogenic controls. A type of continuous disturbance can be rapid base-level rise, while repeated disturbance is most likely associated with the effects of climatic changes on catchment and floodplain. Continuous or repeated disturbance causes relatively high avulsion frequency, leading to continuous coexistence of channels (Fig. 7B–C). On the other hand, in a number of anastomosing river systems, avulsions are not caused by external disturbance of the fluvial system, but rather seem autogenic (e.g. Schumann, 1989; Schumm et al., 1996; Gibling et al., 1998). Little is known quantitatively about avulsion frequencies in these systems, but at least for the Channel Country anastomosing systems they seem to be low (see Section 3.2). Since these systems probably evolve extremely slowly under more or less stable external conditions, they can hardly be taken to represent a state of disequilibrium (Fig. 7D) and seem fundamentally different in process from anastomosing systems caused by external disturbance. At the moment, it may be most appropriate to characterize long-lived anastomosis in general as a state of dynamic equilibrium, with avulsions maintaining a multi-channel system, while older channels are slowly abandoned.

3.5. A conceptual genetic model for long-lived anastomosis

With respect to genesis and lifetime, four basic types of anastomosing rivers have been identified in the preceding sections: (1) short-lived anastomosis within an avulsion belt; (2) short-lived, transitional anastomosis during a single avulsion, due to temporary coexistence of an older trunk channel and a new avulsion channel; (3) long-lived, highly dynamic anastomosing systems, constantly rejuvenated by frequent avulsions caused by allogenic controls; and (4) long-lived, semi-static anastomosing systems, which seem in equilibrium with stable external conditions. Since these four types are morphologically quite similar, anastomosing rivers can be considered an example of equifinality, i.e., different combinations of processes or causes produce a similar form. Consequently, it is hard to define one universal genetic model for anastomosing rivers.

Fig. 7A–C shows how a rise in avulsion frequency results in long-lived anastomosis. An assumption is that channel lifetimes do not decrease strongly with an increase in avulsion frequency. Channel chronologies for anastomosing rivers published by Makaske (1998, his fig. 3.11) and Morozova and Smith (1999, their fig. 8) resemble Fig. 7B–C. Holocene records of avulsion frequency and periods of activity of channels for the Rhine–Meuse delta (Törnqvist, 1994; Stouthamer and Berendsen, unpubl. data) show no systematic changes in periods of activity, along with marked changes in avulsion frequency and the number of coexisting channels, suggesting that the assumption of more or less constant channel lifetimes in Fig. 7A–C is realistic. Thus, avulsion frequency seems to be one of the prime controlling factors of anastomosis. The next question is in which alluvial setting avulsion frequency has its optimum. Below, this question and the relationship between channel morphology (determined by lateral channel stability) and long-lived anastomosis (determined by avulsion frequency) will be explored in a simple conceptual model.

A spatial distribution of alluvial river types which reflects the influence of a downstream reduction in floodplain gradient and a downstream increase in aggradation rate (associated with downstream control) is shown in Fig. 8. The thickness of the bars represents the probability of occurrence of a certain river type as a function of its position on a scale from proximal to distal. Because of a reduction of gradient downstream, lateral channel stability increases as well as avulsion frequency. This leads to a

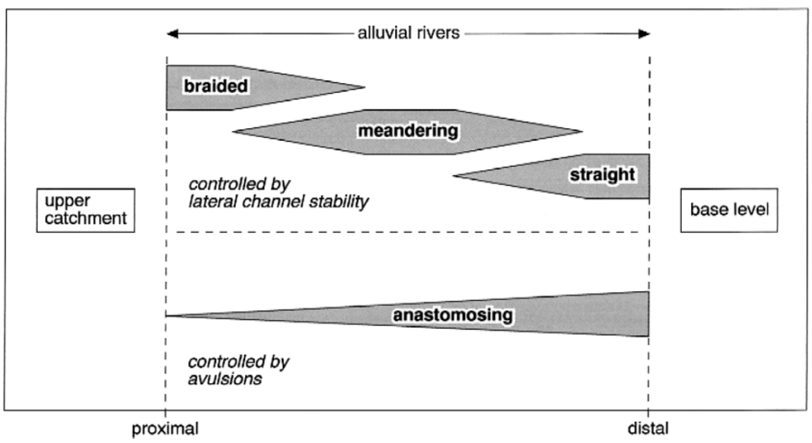


Fig. 8. Spatial distribution of alluvial river types from proximal to distal.

high probability of an anastomosing system composed of straight channels near the mouth. Moreover, conditions of base-level rise may cause a high aggradation rate downstream, and enhance the chance for anastomosis. Upstream, conditions are less favourable for anastomosis. Here, locally high avulsion frequencies on alluvial fans do not cause anastomosing systems.

The relationships among the factors determining the morphology of a fluvial system on an alluvial plain are shown in Fig. 9. Two groups of processes determine the morphology of the river system at the floodplain scale and the channel-belt scale, respectively. At the floodplain scale, the avulsion frequency determines whether or not long-lived anastomosis will occur. Optimum conditions for a high avulsion frequency causing anastomosis obviously exist on a low-gradient floodplain subject to rapid base-level rise forcing rapid aggradation, while ample avulsion triggers exist, such as log and ice jams and a strongly peaked flow regime. At the scale of individual channel belts, lateral channel stability de-

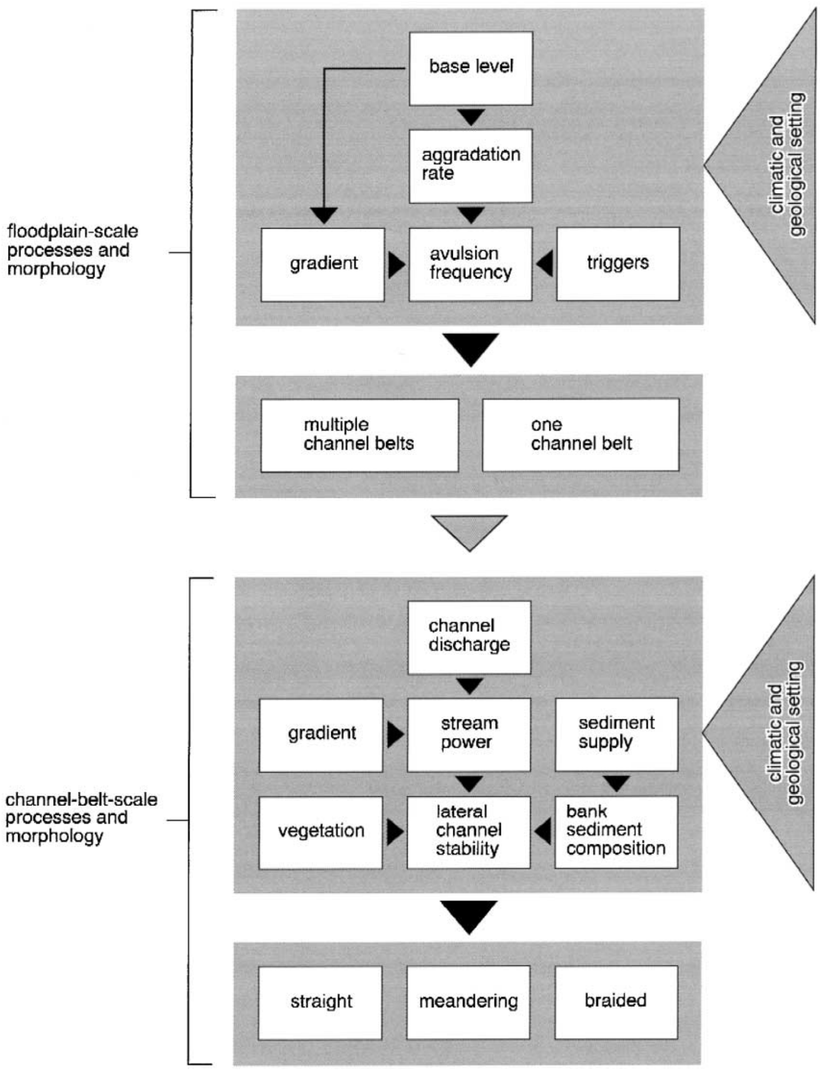


Fig. 9. Conceptual model showing various factors determining the morphology of a fluvial system on an alluvial plain.

termines the place of a channel belt in the braided–meandering–straight sequence. In addition to stream power, lateral channel stability is also strongly influenced by the sediment composition of the banks, which is influenced by the type of sediment supplied by the catchment. Another important factor promoting bank stability is the binding force of vegetation. Since the occurrence of anastomosis determines the discharge per channel and thereby channel stream power, floodplain-scale processes are linked to channel-belt-scale processes. In addition, floodplain gradient is an important factor at both levels.

Concerning the factors 'floodplain gradient' and 'aggradation rate', Table 2 shows essentially two groups of anastomosing rivers: (1) the temperate and tropical humid climate anastomosing rivers which all have high floodplain aggradation rates, while some of the gradients are relatively high as well; (2) the arid, semi-arid and subarctic anastomosing rivers, which show low floodplain aggradation rates or incision as well as relatively low gradients. It should be stated that the number of modern anastomosing rivers studied is much too low to allow a generalization of the suggested relationships between climate, floodplain aggradation rate, and channel gradient. Nevertheless, the reported modern anastomosing rivers either have: (1) low gradients; (2) high floodplain aggradation rates; or (3) both. In the latter case, conditions for anastomosis according to the presented conceptual model are optimal. In the first two cases, conditions for anastomosis seem to be less favourable. The role of factors now grouped as 'triggers' is thought to be especially relevant for those anastomosing rivers. At present, these factors are still poorly documented. Additionally, in a number of anastomosing river systems, in-channel aggradation (not necessarily associated with rapid base-level rise) may be much more important than floodplain aggradation as a driving force of avulsions. However, very few data exist on rates of in-channel aggradation.

Thus, it is clear that the presented model does not equally well explain the origin of all types of long-lived anastomosing rivers. Long-lived, semi-static anastomosing systems (Fig. 7D) that exist under stable external conditions, do not seem to depend on a high avulsion frequency. Very slow abandonment of older channels and low sediment load are important features of these systems. Nanson and Huang (1999) proposed a hydraulic explanation for this type of anastomosing river. For the geological record, however, the importance of long-lived, frequently avulsing anastomosing rivers is paramount, since these systems tend to be rapidly aggrading and produce thick sequences of anastomosing river deposits.

4. The sedimentary facies of anastomosing river systems

4.1. Introduction

The deposits of anastomosing rivers can be expected to be relatively abundant in the stratigraphic record due to high aggradation rates in many anastomosing river systems. Identification of ancient anastomosis gives important clues for interpretation of the large-scale palaeogeographical setting (Galloway and Hobday, 1983, p. 51). In this part of this paper, I will deal with the question how we can recognize the deposits of anastomosing rivers in the stratigraphic record. This requires analysis of their alluvial architecture as well as their sedimentary facies.

The term 'fluvial architecture', nowadays more commonly termed 'alluvial architecture', was introduced by J.R.L. Allen "...to encompass the geometry and internal arrangement of channel and overbank deposits in a fluvial sequence" (Miall, 1996, p. 34). The term 'facies' is used in a purely descriptive sense in this paper, following the definition of Reading (1996, p. 19): "A rock facies is a body of rock with specified characteristics. (...) If fossils are absent or of little consequence and emphasis is on the physical and chemical characteristics of the rock, then the term lithofacies is appropriate".

4.2. The sedimentary environments and lithofacies of modern anastomosing river systems

Above, different genetic types of anastomosing rivers have been identified (Sections 3.4 and 3.5). These different types partly generate different deposits, with respect to lithofacies as well as alluvial architecture. Additionally, differences in climatic setting provide another fundamental control on the character of anastomosing river deposits. Just as it is impossible to present one genetic model for anastomosing rivers, it is also impossible to present one universal facies model for anastomosing rivers. The types of anastomosing river settings with associated lithofacies that will be discussed below by no means give a complete picture of the full range of anastomosing river sedimentary environments. They only represent what already has been discovered, after investigation of a limited number of modern examples. Especially with respect to sedimentary structures, information is still scarce; most studies predominantly present textural facies.

4.2.1. Short-lived anastomosis within an avulsion belt

The deposits associated with anastomosing channels within an avulsion belt were only described from the lower Saskatchewan River (Smith et al., 1989; Smith and Pérez-Arlucea, 1994; Pérez-Arlucea and Smith, 1999). At present, it is still unclear to what extent the occurrence of this type of anastomosing river sedimentary environment is tied to the specific setting of the lower Saskatchewan River: a wide, rapidly aggrading floodplain in a temperate humid climate. Sedimentation rates of this system are strongly variable in time and space ranging from 0.87–1.67 mm/year for subrecent peat and organic-rich deposits away from active channels (Morozova and Smith, 1999, their table 1) to 33 mm/year, locally in the recent avulsion belt (Smith et al., 1989, p. 20).

The avulsion-belt deposits of the lower Saskatchewan River show wide textural variation, reflecting proximal–distal relationships, location of avulsion channels, sediment supply, and the stage of development of the avulsion. Sandy crevasse splay deposits (see Section 4.2.2 for description) are common depositional units near the trunk channel and avulsion channels. Away from channels and in more distal parts of the avulsion belt, the lens-shaped body of avulsion-belt deposits is predominantly built up of silt, underlain and often capped by organic-rich deposits. Vertically, these silty deposits, which are volumetrically dominant over sandy avulsion-belt deposits, are characterized by a coarsening-upward sequence. Coarsening-upward units of a similar origin, although typically more rich in sand, were described by Elliott (1974) from deltaic interdistributary bays. Close to the avulsion channels, natural levee deposits rest on top of avulsion-belt deposits.

Avulsion channels may form a temporary anastomosing network within the avulsion belt (Fig. 4). Infilling of these channels with sandy bedload results in stringers of sandy channel deposits, which are inset in the predominantly silty body of avulsion-belt deposits (Fig. 10). During progradation of the avulsion belt, deposition of a thick fine-grained sequence precedes scour of avulsion channels. Many of the anastomosing avulsion channels are abandoned before they have scoured through the base of the thick avulsion deposits. Hence, their sandy channel-fills are fully surrounded by finer avulsion-belt deposits. This is an important diagnostic feature of this type of anastomosing river deposits. Nevertheless, bigger avulsion channels may scour into the pre-avulsion deposits.

Sand bodies within the avulsion-belt deposits show a great variety in shapes and sizes. Channel-fills tend to be ribbon-shaped with width/thickness ratios $<$ 10. Their thickness is typically 1–3 m, although some exceed 7 m. Laterally extensive [up to nearly 1 km wide (N.D. Smith, personal communication, 2000)], sometimes discontinuous sand sheets represent crevasse splays and channel mouth bars. Typical thicknesses are 0.5 to 2 m (Pérez-Arlucea and Smith, 1999).

The avulsion of the lower Saskatchewan River in the 1870s has affected over 500 km^2 of wetlands up to today (Smith et al., 1998), with avulsion-belt deposits up to 3.5 m in thickness. This suggests that avulsion-belt deposits may be a volumetrically important element of the floodplain deposits of long-term aggrading, avulsive river systems.

4.2.2. Long-lived, rapidly aggrading anastomosing rivers in a humid setting

Despite differences in scale and geological setting, humid climate, rapidly aggrading anastomosing rivers show remarkable similarity in sedimentary environments and lithofacies. A widely used lithofacies model for this type of anastomosing rivers is mainly based on a few well-documented examples in western Canada. A major difference with the model

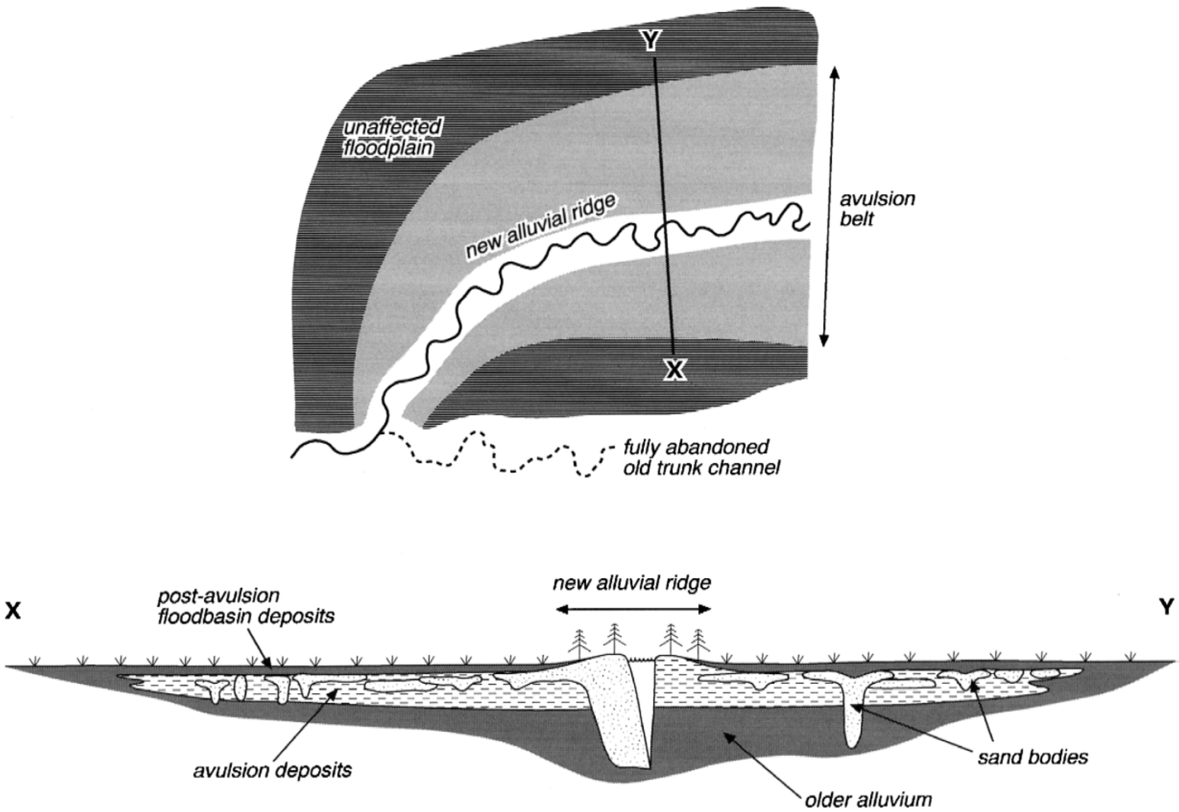


Fig. 10. Hypothetical section across a former avulsion belt where a new trunk channel has established, based on field evidence from the lower Saskatchewan River. The cross-section shows avulsion deposits sandwiched between older alluvium and a thin veneer of post-avulsion materials derived from a new alluvial ridge. Avulsion deposits are predominantly silty and clayey sediments enclosing variously shaped and sized sand bodies formed by splays (thinnest), anastomosing channels (thicker) and the final new alluvial ridge (thickest) (after Smith et al., 1989).

discussed above is that anastomosis in this model is not the product of a single avulsion, but a result of repeated avulsions driven by continuous rapid floodplain aggradation. Other important elements of this model are abundant bank vegetation and erosion-resistant peat layers, promoting lateral channel stability.

The investigated rivers in western Canada include the Alexandra, North Saskatchewan, Mistaya, upper Columbia and lower Saskatchewan Rivers, which show average floodplain aggradation rates between 0.6 and 1.8 mm/year. These are mainly relatively small-scale rivers in a proximal, montane setting with abundant sediment supply to a narrow confined floodplain, where local base level is controlled by cross-valley alluvial fans. An exception is the lower Saskatchewan River, which is rather a medium-scale river with a wide floodplain. Besides well-developed anastomosis within the recent avulsion belt (see Section 4.2.1), the lower Saskatchewan River also displays a larger-scale anastomosing pattern, caused by repeated avulsion during the middle and late Holocene, resulting in long-term coexistence of multiple channel belts (Morozova and Smith, 1999, their Fig. 8). Initially, downstream increasing isostatic rebound was believed to be a major cause of Holocene floodplain aggradation of the Saskatchewan River (e.g. Smith, 1983); however, Morozova and Smith (1999) argued that since 5400 BP differences in isostatic rebound have been insignificant.

In the first anastomosing river facies model (Smith and Smith, 1980), it is shown how rapid vertical accretion in combination with restricted lateral movement of channels produces a network of thick and narrow sand bodies in the subsurface (Fig. 11). The sand bodies are embedded in (sometimes organic) floodbasin fines, and the lateral lithological boundaries are rather abrupt. It is now realized that the vertical scale of this diagram is exaggerated far too much to give a realistic picture (D.G. Smith, personal communication, 1998).

In later publications, the core of the model remained unchanged, although it became recognized that crevasse splay deposits and avulsions were crucial elements (Smith, 1983; Smith et al., 1989). The role of avulsion was a significant addition to the model since this prevents the channel deposits from reaching unrealistic thicknesses, as was suggested in Fig. 11. An improved textural facies diagram was recently published by Makaske (1998) (Fig. 12).

On the basis of the research in western Canada, six anastomosing river sedimentary environments and associated lithofacies were identified (e.g. Smith, 1983). The lake, marsh and mire environments and facies are laterally extensive and show little variability. These facies were estimated to make up 60% to 90% (Smith, 1983) of anastomosing river deposits. The channel-related environments and facies are laterally more restricted and internally more complex.

Aggradation in anastomosing *channels* can result in channel-fills that are remarkably thick [5–12 m in the Columbia River (D.G. Smith, personal communication, 1998)] and relatively narrow. Width/thickness ratios of around 7 (Makaske, 1998, p. 72) and 11 (Smith, 1986, p. 186) were reported for recently formed channel sand bodies in the upper Columbia River. In lateral and vertical direction, channel deposits change abruptly into finer grained overbank deposits. The channel-fill deposits range from gravel (Smith and Smith, 1980) to silt (Smith, 1975), but predominantly they consist of sand. Sets of planar tabular cross beds result from deposition by migrating sand waves. In addition, multi-storied fining-upward textural sequences were identified, which were interpreted as flood cycle deposits during channel aggradation. The above-mentioned characteristics typify the fills of commonly occurring, vertically infilling, laterally stable anastomosing channels. Nevertheless, small-scale (1 m thick) sets of inclined heterolithic stratification (IHS), produced by narrow laterally accreting point bars, were found locally in the channel-fills of the upper Columbia River (Smith, 1983; Thomas et al., 1987, p. 138). In the lower Saskatchewan River, lateral point bar accretion is probably much more widespread since bigger mature channels of this anastomosing system show a tendency towards meandering. This will result in channel sand bodies with width/thickness ratios much greater than the values mentioned above. Although not being typical, and therefore not included in the 'classic' facies model, it should be realized that such meandering channel elements may well be part of

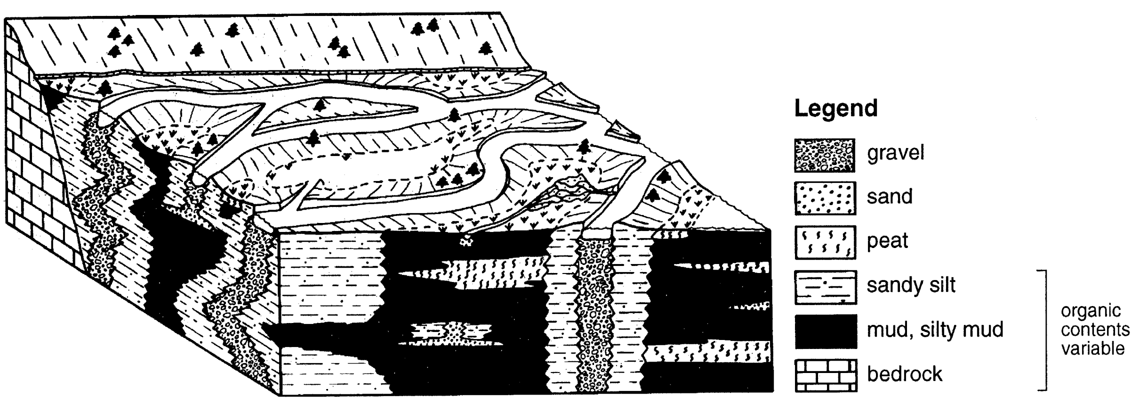


Fig. 11. Textural facies model of a rapidly aggrading anastomosing river system, in a temperate humid, montane setting (from Smith and Smith, 1980; ©SEPM, reprinted by permission).

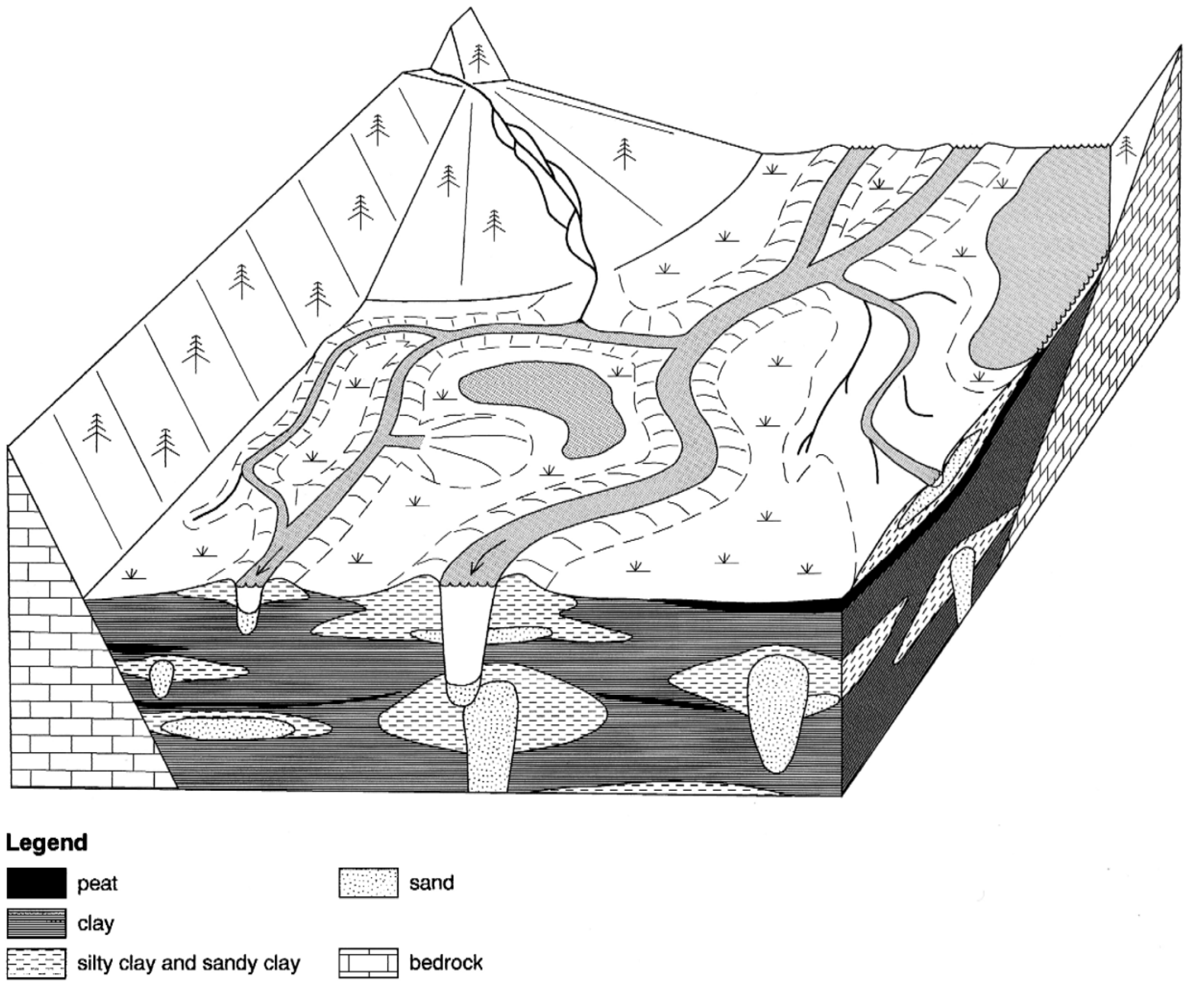


Fig. 12. Textural facies model of the upper Columbia River (British Columbia, Canada), a rapidly aggrading anastomosing system in a temperate humid, montane setting. Area shown measures ~2 km in width. Vertical scale strongly exaggerated; thickness shown ~10 m (from Makaske, 1998).

anastomosing river deposits, since anastomosis does not exclude meandering (or even braiding) of individual channels within the anastomosing network (see also Section 2.3). Makaske (1998, pp. 219–226) interpreted subrecent anastomosing channel-fills on the humid coastal plain of the Rhine–Meuse delta to represent various modes of vertical and lateral accretion, including lateral concave-bank bench accretion as described by Hickin (1979, 1986) and Page and Nanson (1982).

The *natural levees*, which flank the channels, are wedge-shaped in cross-section. They consist of laminated fine sand and silt, which fine and taper out laterally in floodbasin deposits. These sediment bodies can be up to 4 m thick (Smith, 1983, p. 163) and 2 km wide (N.D. Smith, pers. commun., 2000) in the lower Saskatchewan River. Usually, they are topped by floodbasin deposits such as lake or marsh deposits, or peat. Directly underneath levees, however, avulsion-belt deposits (Fig. 10) may be present, referring to the origin of the associated channel.

Crevasse splays are deposited in the floodbasin, adjacent to spots where the natural levee is dissected by a small channel drawing flow from the main channel. Being deposited by miniature fluvial systems, their structure, texture and geometry tends to be very complex. Their planform is generally lobate but can be highly irregular. In cross-section, crevasse splays are lens-shaped and up to 3 m thick. They show a coarsening-upward sequence at the base and a thin fining-upward sequence at the top. Their texture ranges from coarse silt to coarse sand with granules. Cross-lamination as well as high-angle cross-beds are the internal structures of the sandy deposits. Usually, crevasse splay deposits are sandwiched between floodbasin muds or peat in a conformable fashion; however, crevasse channels may incise through the splay deposits into the subsurface, while taking over a substantial portion of the flow of the trunk channel. This process may herald formation of a new channel belt in the anastomosing river system. In the lower Saskatchewan River this involves the evolution of the crevasse splay into a highly complex avulsion belt (see Section 4.2.1). However, in most cases the feeding crevasse channel becomes plugged up again after some time and the crevasse splay is abandoned and invaded by vegetation.

Marshes, *lakes* and *mires* are wetland environments with a low bottom elevation relative to the natural levees and crevasse splays. In lakes and marshes, suspended load is deposited, while mires generally are too remote from the channels to receive significant amounts of clastics. Marsh deposits consist of organic and clastic mud. They may be laminated, but usually they are bioturbated. Lake deposits consist of laminated clay and silt, although bioturbation may also have destroyed any structure. Mires are extensive and contain peat up to 3.5 m in thickness in the Saskatchewan marshes. However, development of peat strongly varies among the investigated humid climate anastomosing rivers, predominantly depending on influx of clastics in relation to floodplain width. In proximal montane settings with abundant supply of clastics to a narrow floodplain, for example in the upper Columbia River, mires are rare and short-lived, resulting in few thin peat beds (Fig. 12).

The cited examples from western Canada were the first detailed descriptions of anastomosing river sedimentology and therefore have set the standard. However, these anastomosing systems represent a biased dataset, as they are all located in temperate humid continental settings and represent small to medium-scale anastomosing rivers.

Research in the tropical humid large-scale anastomosing system of the Magdalena River in Colombia (Smith, 1986), showed that 'the model from western Canada' has a more universal applicability. A remarkable feature revealed by deep boreholes (up to 55 m) was the vertically uniform trend in mean grain size of buried Magdalena channel-fills, which was attributed to dominant vertical accretion of the channel deposits. Lateral accretion would have resulted in a fining-upward trend. The common occurrence of organic litter is another typical feature observed in the Magdalena channel deposits. Mud interbeds seemed to be absent in the boreholes, but mud balls were found in grab samples from the channel beds. The overbank deposits of the Magdalena generally contain only thin accumulations of organic material, in contrast to the overbank deposits of the lower Saskatchewan River. This was attributed to the high clastic input associated with the foreland basin setting of the system. The Magdalena River floodplain has a very high average long-term aggradation rate of 3.8 mm/year (Table 2) over 7500 radiocarbon years. Rapid aggradation is believed to be more or less equal to tectonic downwarping of the foreland basin.

4.2.3. *Long-lived, slowly aggrading anastomosing rivers in an arid setting*

Not all anastomosing river deposits comfortably fit into the models described above. Especially some long-lived, slowly aggrading anastomosing rivers in arid climates show major differences in sedimentary environments and lithofacies. Although a number of such anastomosing rivers has been identified, comprehensive descriptions of sedimentary environments and lithofacies are presently only available for Cooper Creek in central Australia and the upper Inland Niger Delta in central Mali. Geologically, both systems have a roughly comparable distal, intracratonic setting. Nevertheless, differences in tectonic control result in differences in sedimentation rates: the tectonically stable Cooper Creek floodplain aggrades at 0.04 mm/year, while the slowly subsiding Inland Niger Delta aggrades at 0.14 mm/year (Table 2).

Work of Rust (1981) on the arid Cooper Creek anastomosing system revealed the following important differences with 'the model from western Canada': (1) a lower proportion of channel sands relative to overbank fines, due to lower channel density; (2) less organics in the overbank sediments due to much lower plant growth; (3) absence of crevasse splay deposits and fewer levee deposits, since levees are subtle and discontinuous. Rust (1981) described the channel-sands as isolated sand stringers encased in a predominantly muddy sequence. Internally, the sand bodies typically showed planar cross-stratification resulting from deposition as alternating side bars, underlain by trough cross-stratified sand and capped by horizontally and ripple-laminated sand. The mud was commonly structureless due to bioturbation and alternate shrinkage and swelling. Duricrusts and evaporite horizons occurred in addition to abundant desiccation cracks.

Rust's model was extended by Gibling et al. (1998), who provided many details about the Cooper Creek sediments. They showed that the Cooper Creek channel bodies essentially comprise mud-rich channel-fills that are sandier towards their bases. They reported lateral and vertical accretion of the channel deposits, often in the form of accretionary benches with inclined heterolithic stratification [IHS as defined by Thomas et al. (1987)] at higher levels. The dimensions of the muddy channel bodies can be up to 7–10 m thick and >100 m wide. Width/thickness ratios of these bodies were estimated at >15 and possibly 100 or more, based on limited data. Notably heterolithic anastomosing channel-fills were also described by Taylor and Woodyer (1978) and Woodyer et al. (1979) from semi-arid eastern Australia. The heterolithic benches can be found at different levels in the channel. The lower benches are characterized by cross-bedded fine sands with mud interbeds, while the upper benches consist of interlaminated sands and muds.

Makaske (1998) reported thick (4–5 m) vertically accreted clayey upper parts of channel-fills in the semi-arid upper Inland Niger Delta. Sandy deposits in the lower part of the channel-fills were formed during an earlier phase of predominantly lateral accretion. Aeolian dune deposits are abundant in this anastomosing system, in the channels as well as on the floodplain. Aeolian sediments also occur as an admixed silt/sand fraction in the clayey floodbasin deposits. Levees and crevasse splays are relatively fine-grained in this system. In Fig. 13 the sedimentary environments and textural facies of the upper Inland Niger Delta are summarized. This diagram is not intended to be a universal facies model for long-lived, slowly aggrading, arid anastomosing rivers, but is shown here rather as an example of an alternative anastomosing river facies model.

With very few modern examples investigated, generalizing about the sedimentary environments and lithofacies of long-lived, slowly aggrading, arid anastomosing rivers is unjustified. Another more fundamental problem is that Quaternary climatic oscillations in combination with slow aggradation rates prevented formation of thick sequences produced by such anastomosing rivers under equilibrium climate conditions. Therefore, in modern and subrecent environments there is no opportunity to check our assumptions of what these sequences will look like.

4.2.4. *Other long-lived anastomosing rivers*

It is clear from the above that the sedimentology of long-lived, slowly aggrading, arid anastomosing rivers still needs attention, since it is unclear how representative the examples studied to date are. Besides that, some anastomosing river settings have never or barely been studied sedimentologically. In particular, we lack information about cold-climate anastomosing rivers. Plan views from, for example, the Ob and Mackenzie Rivers, suggest that extensive anastomosing river systems exist in the subarctic zone.

Currently, the only sedimentologically studied subarctic anastomosing river is the Attawapiskat River in central Canada (King and Martini, 1984). Since this river is incising estuarine clays and Pleistocene tills that are uplifted due to istostatic rebound, only thin accumulations of anastomosing river deposits occur in this setting. Channel deposits in main channels principally consist of thin boulder and pebble lags over shoals eroded in underlying till, and junction bars (downstream from islands) mainly consisting of sorted coarse to medium-sized sand, showing well-developed fining upward. In secondary channels, only thin silt and clay drapes erosively overlie the hard substratum. Levees mainly consist of

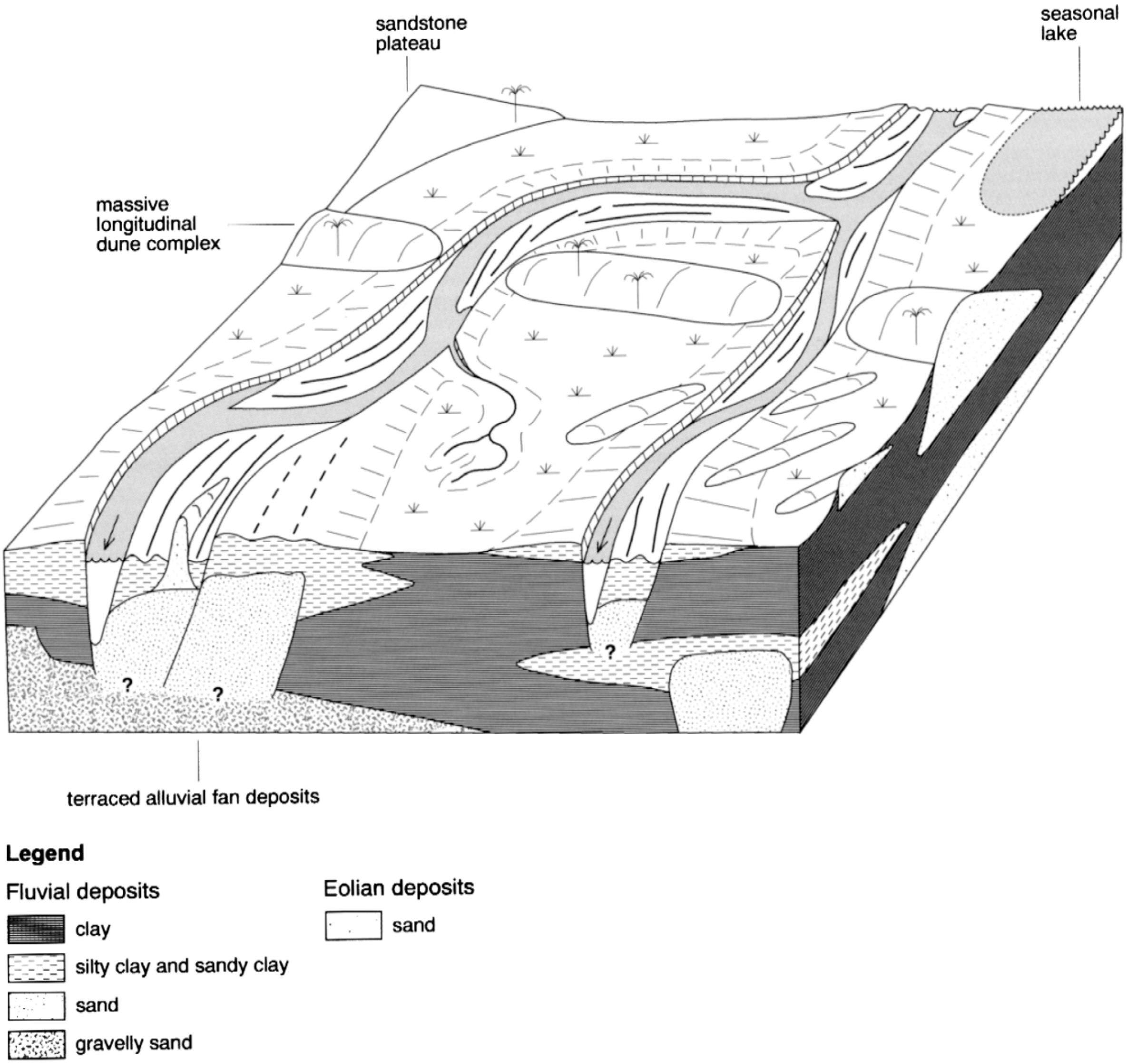


Fig. 13. Textural facies model of the upper Inland Niger Delta, a slowly aggrading anastomosing river system in a semi-arid climatic setting. Area shown measures ∼40 km in width. Channel belts are oversized for clarity. Vertical scale strongly exaggerated; thickness shown ∼10 m. Remarkable features are the abundant aeolian lithofacies originating from formation of different types and generations of dunes, and the relatively fine-grained channel deposits filling up oversized channels (from Makaske, 1998).

laminated silt, while marshes show regular alternation of silt with organic-rich layers. Further away from the channels, mires exist with up to 0.5 m thick grassy peat. Peat may also fill up abandoned secondary channels. Important climatic indicators are the considerable amounts of ice-rafted sand and pebbles in the overbank sediments. Remarkably, crevasse splays are absent in this system, although frequent ice jams in the lower reaches cause flooding and overbank sedimentation.

Since the preservation potential of the deposits described by King and Martini (1984) is extremely low, from a sedimentological point of view it would be more interesting to investigate long-term aggrading, subarctic anastomosing rivers in subsiding settings. However, these may be scarce due to post-glacial isostatic rebound in most subarctic regions. Other gaps in our sedimentogical knowledge concern rapidly aggrading arid anastomosing rivers and slowly aggrading humid anastomosing rivers, but these types of anastomosing rivers are probably less common than the types of anastomosing rivers studied hitherto.

4.3. The lithofacies of interpreted ancient anastomosing river systems

Knowledge on the sedimentology of modern anastomosing systems was first applied to ancient fluvial deposits by Le Blanc Smith and Eriksson (1979), Smith and Putnam (1980) and Putnam and Oliver (1980). At that time, still relatively little was known in detail about anastomosing river lithofacies, and consequently the validity of these early interpretations has been questioned later. Especially the work

Table 3
Alluvial–architectural characteristics of interpreted subrecent and ancient anastomosing river systems

Study location and data source	Proportion of overbank deposits (in %)	Laterally connected channel sandstone bodies[a]	w/t [b] of channel sandstone bodies
Clifton Fm. (New Brunswick, Canada)[1]	70	unknown	≤ 73
Ft. Union Fm. (Wyoming, U.S.A.)[2]	45	yes	67
Ft. Union Fm. (Wyoming, U.S.A.)[3]	50–90	unknown	10
Cumberland Group (Nova Scotia, Canada)[4]	70	unknown	3–38
Tatrot/Pinjor Fm. (India)[5]	65	unknown	≥ 7–26
Wasatch Fm. (Wyoming, U.S.A.)[6]	80	yes	105–165
Raton Fm. (Colorado/New Mexico, U.S.A.)[7]	75	unknown	2–120
Vrijheid Fm. (South Africa)[8]	no data	yes	50–500
St. Mary R. Fm. (Alberta, Canada)[9]	85	inferred	8–27
Pitalito Basin (Colombia)[10]	no data	yes	no data
Cutler Fm. (New Mexico, U.S.A.)[11]	75	yes	≤ 40
Dakota Fm. (Utah, U.S.A.)[12]	60	unknown	7–20
Betuwe Fm. (The Netherlands)[13]	90	yes	5– ≥ 67
Brazeau/Belly R. Fm. (Alberta, Canada)[14]	no data	yes	10
Willwood/Ft. Union Fm. (Wyoming, U.S.A)[15]	70	yes	< 10
Riverine Plain (New South Wales, Australia)[16]	no data	yes	70–1000

[a] Planform pattern shows bifurcation and/or convergence of sandstone bodies.
[b] Width/thickness ratio.
[1] Rust and Legun (1983).
[2] Flores and Hanley (1984).
[3] Johnson and Pierce (1990).
[4] Rust et al. (1984).
[5] Kumar and Tandon (1985).
[6] Warwick and Flores (1987).
[7] Flores and Pillmore (1987).
[8] Cairncross et al. (1988).
[9] Nadon (1988, 1994), Currie et al. (1991).
[10] Bakker et al. (1989).
[11] Eberth and Miall (1991).
[12] Kirschbaum and McCabe (1992).
[13] Törnqvist et al. (1993), Törnqvist (1993a), Makaske (1998).
[14] Putnam (1993).
[15] Kraus (1996), Kraus and Gwinn (1997), Kraus and Wells (1999).
[16] Page and Nanson (1996).

on the Mannville Formation (Smith and Putnam, 1980; Putnam and Oliver, 1980; Putnam, 1982, 1983), which heavily relied on interpretation of geophysical subsurface data, has given rise to alternative interpretations (Wightman et al., 1987; see also Miall, 1996, p. 279). Later, more convincing outcrop studies were published (Rust and Legun, 1983; Flores and Hanley, 1984; Rust et al., 1984), and at present there is a number of well-described ancient fluvial sequences that are believed to be of anastomosing river origin (Table 3). The lithofacies and facies geometries of these ancient systems will be dealt with together in this section. Besides 'true' ancient examples, a few subrecent anastomosing river systems are also included in this review (e.g. Bakker et al., 1989; Törnqvist, 1993a).

4.3.1. Sandstone facies

Two geometric types of sandstone facies are distinguished: ribbon bodies and tabular bodies.

The ribbon bodies are characterized by a sharp, scoured, often concave base and a gradational or sharp flat top (Fig. 14). Their thickness is usually a few metres, but may be up to tens of metres (e.g. Warwick and Flores, 1987). Normally, they have a width in the order of tens to hundreds of metres. Internally they either show fining upward (e.g. Flores and Pillmore, 1987; Cairncross et al., 1988; Kirschbaum and McCabe, 1992) or they are relatively homogeneous in texture (e.g. Rust et al., 1984; Johnson and Pierce, 1990; Törnqvist et al., 1993; Nadon, 1994). Grain size ranges from coarse to fine sand. Conglomerate sometimes constitutes a lag near the erosional base of those bodies (e.g Flores and Hanley, 1984; Warwick and Flores, 1987; Eberth and Miall, 1991). These lags may contain fragments of mudstone, petrified wood, or coal. In some cases, the ribbon bodies are less sandy and have a notably heterolithic composition of interbedded sandstones, siltstones and mudstones (Kirschbaum and McCabe, 1992). Ribbons may consist of multiple stories, separated by erosion surfaces (Kraus, 1996). The dominant sedimentary structure is trough cross-bedding with subordinate planar cross-bedding, while near the top of the bodies ripple or climbing-ripple lamination is usually present. The cross-bedded sets may be up to 1.2 m thick. Lateral accretion stratification is not a consistent feature of these sandstone bodies, but occasional examples are reported (Rust and Legun, 1983; Rust et al., 1984; Warwick and Flores, 1987; Kirschbaum and McCabe, 1992; Nadon, 1994; Makaske, 1998, pp. 201–202). Some of these exam-

Fig. 14. Ribbon sandstone body in the St. Mary River Formation (Alberta, Canada). The ribbon has a sharp concave base and a flat top, and is approximately 50 m wide. Width/thickness ratio is around 12. This sandstone body is interpreted as channel-fill deposits of an ancient anastomosing river system (Nadon, 1994).

ples can be classified as inclined heterolithic stratification, due to the presence of mudstone drapes.

The tabular bodies typically have flat, non-erosive bases and either sharp or gradational lower and upper contacts. Their thickness is usually limited to a few metres and often they are less than 1 m thick. Laterally, however, they can be hundreds to thousands of metres wide before grading into finer-grained deposits. Documented vertical textural trends include: (1) upward fining (Nadon, 1994); (2) upward coarsening (Flores and Pillmore, 1987; Warwick and Flores, 1987); (3) upward coarsening followed by upward fining (Rust and Legun, 1983; Rust et al., 1984); and (4) no vertical trend at all (Johnson and Pierce, 1990). The sand grain size may be coarse, but it is usually medium to fine, grading to silt. The dominant structures are ripples, climbing-ripples and parallel laminations, with occasional small-scale trough cross-beds and wave-ripple lamination (e.g. Nadon, 1994). The tops of these bodies are often heavily rooted and bioturbated and may show traces of palaeosol formation (e.g. Johnson and Pierce, 1990).

The ribbon sandstone bodies are commonly interpreted as channel-fills, while the tabular bodies are taken as crevasse splay or levee deposits. The levee deposits may be heterolithic and display mudrock partings (Johnson and Pierce, 1990). Frequently, the tabular bodies are attached like 'wings' (Fig. 15) to the top of ribbon sandstone bodies (Eberth and Miall, 1991; Kirschbaum and McCabe, 1992; Nadon, 1994; Kraus, 1996). Kraus (1996, p. 361) proposed two origins for the wings of relatively small ribbon sandstone bodies: (1) deposition by sheet floods from a main channel, resulting in lobate sandy crevasse splay deposits, which are later scoured by developing crevasse splay channels (represented by the ribbons); (2) overbank deposition from crevasse splay channels during the final infilling of the channel. Wings originating from the latter process may be considered as levee deposits. Kraus, also reported 'tiers', i.e., laterally extensive sheet-like sandstone bodies that connect the tops of multiple stratigraphically equivalent ribbon sandstones. This suggests an origin as crevasse splay with multiple coexistent crevasse channels. Facies architecture and types and arrangement of palaeosols strongly favoured interpretation of such complexes as avulsion-belt deposits (Kraus, 1996; Kraus and Gwinn, 1997; Kraus and Wells, 1999), analogous to the deposits found in parts of the recent avulsion belt of the lower Saskatchewan River (Smith et al., 1989). Nadon (1994, his Fig. 8) also

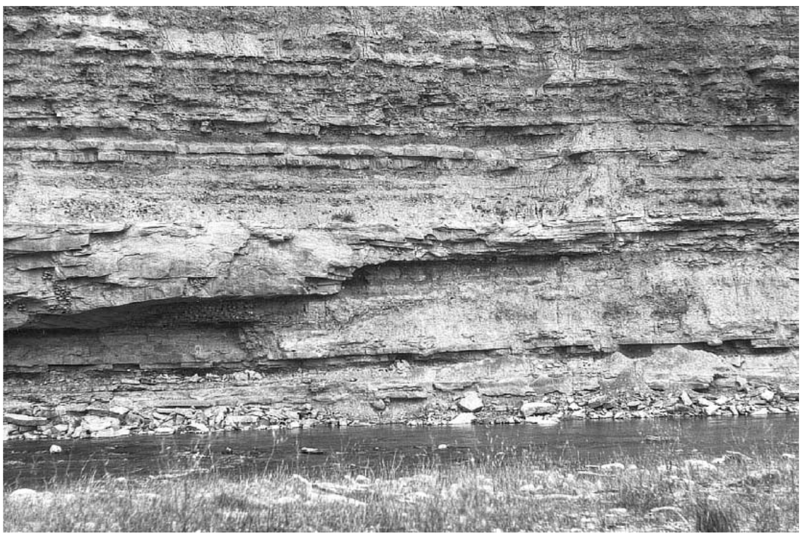


Fig. 15. Close-up of lateral wing attached to the right-hand margin of the ribbon sandstone body of Fig. 14. The wing is capped by a sequence of weathered mudrock sheets and erosion-resistant tabular sandstone bodies (positive relief). The upper part of the sandstone ribbon gradually passes into the wing. The wing is interpreted as levee deposits, whereas the tabular sandstone bodies are believed to represent crevasse splay deposits (Nadon, 1994).

described channel sandstone ribbons with lateral sandstone wings. Although he interpreted the wings as levee deposits, the fact that the wings partly also underlie the erosive base of the channel sand body, rather indicates a crevasse splay origin for the wings, with subsequent channel scour and infilling. In other cases, the top of the sandstone body gradually passes into the wing (e.g. Fig. 15), suggesting a levee origin for the wing.

Although natural levee and crevasse splay deposits may be preserved as sandstone bodies, it should be reminded that these deposits in modern anastomosing river environments also have important fine-grained components, which are part of the mudrock facies (Smith and Pérez-Arlucea, 1994). Another point is that the ribbon sandstone bodies may not represent all channel facies, as channels sometimes fill in with mud rather than sand (e.g. Page and Nanson, 1996). Thick muddy sequences may occur along the margins of channel sandstone bodies due to concave-bank bench accretion associated with confined meandering of palaeochannels in anastomosing systems (Makaske, 1998, pp. 225–226).

4.3.2. Mudrock facies

In this paper, the term mudrock is used, following Lundegard and Samuels (1980), for a sedimentary rock which consists for more than 50% of grains finer than sand. Depending on silt–clay content, siltstones, mudstones, or claystones can be distinguished.

Usually in ancient anastomosing systems, the mudrock facies strongly dominates over the sandstone facies. Mudrock beds have a sheet-like appearance (Fig. 15), and the sheets are bounded or split by sandstone or coal facies. The thickness of the sheets is highly variable and may range up to 20 m (Eberth and Miall, 1991). Alternatively, mudrock may be present as plugs overlying ribbon sandstone bodies (e.g. Rust and Legun, 1983). Eberth and Miall (1991) also reported U-shaped mixed-fill units, comprising abundant laminated mudrock over relatively thin basal (pebbly) sandstone.

The mudrocks usually consist of interbedded siltstone, mudstone, and claystone. The individual beds are either massive or horizontally laminated. The siltstone portion of the mudrock facies may be current or wave-ripple laminated, and laminae of fine sand may locally be present. The colours range from grey and green to yellow, brown and red (e.g. Kumar and Tandon, 1985). Grey and green mudrock may contain organic material like leaves, wood fragments and seeds. Additionally, dark coaly intervals are typical for this type of mudrock facies. In contrast, yellow, and red mudrocks usually lack organics, but can have calcrete nodules or horizons (e.g. Rust and Legun, 1983; Kumar and Tandon, 1985). Desiccation cracks of 1 m deep were found in this type of mudrock facies (Rust and Legun, 1983). In general, root mottling and burrows are common characteristics of mudrock facies and are often found in association with incipient palaeosols, which can be traced laterally in the sheets over long distances. Based on pedogenic characteristics, Kraus and Aslan (1993) separated mudrocks into two categories. They distinguished mudrocks with cumulative palaeosols and mudrocks with simple (noncumulative) palaeosols. Cumulative palaeosols tend to be well-developed and typify massive claystones, whereas simple palaeosols show much weaker profile development in more heterogeneous mudrocks consisting of alternating claystone, mudstone and sandstone (Kraus, 1996; Kraus and Wells, 1999).

The mudrock facies is usually interpreted to represent a number of depositional environments. Interlaminated wedges of siltstones and mudstones adjacent to ribbon sandstone bodies are assumed to be levee deposits, while lenses of siltstone and mudstone, sandwiched between claystone beds, are likely to represent crevasse splay deposits or avulsion-belt deposits (see next paragraph). More finely laminated and possibly wave-rippled mudrock is usually taken as lacustrine deposits (e.g. Nadon, 1994). Faunal or palaeobotanical evidence (e.g. Van der Woude, 1983, 1984) can be necessary to give this interpretation a firmer basis, as bioturbation may have destroyed the primary structures. Often, rather structureless and bioturbated (perhaps mottled) mudrock is assumed to be a marsh deposit (cf. Smith, 1983).

Interpretation of palaeosols in mudrock may provide relative indications of sedimentation rates. The cumulative palaeosols distinguished by Kraus and Aslan (1993) were interpreted to result from concurrent pedogenesis and deposition, indicating that deposition rate was slow enough to incorporate thin increments of freshly deposited material into the developing soil profile. On the contrary, simple palaeosols were believed to relate to rapid sedimentation, preventing cumulative soil development. In this case, each soil profile represents a single depositional episode, which was followed by a period of pedogenesis. Based on these pedological interpretations and the arrangement of the sand bodies with respect to the palaeosols, simple palaeosol units could be attributed to avulsion-belt and/or levee deposition (Kraus, 1996; Kraus and Gwinn, 1997; Kraus and Wells, 1999). In this model, cumulative palaeosol units represent overbank deposits formed far from major channels and avulsion belts [including for example the marsh deposits as described by Smith (1983)]. An example of subrecent fine-grained avulsion-belt deposits associated with anastomosing ribbon sand bodies in a deltaic setting was presented by Makaske (1998, pp. 220–223). In this case, the lens of predominantly clayey avulsion-belt deposits is sandwiched between peat layers. Likewise, a neighbouring subrecent anastomosing system with comparable deposits and facies architecture earlier described by Törnqvist et al. (1993) can now be interpreted as an abandoned avulsion belt.

Mudrock plugs are commonly interpreted as abandoned channel deposits based on geometry, because lithologically they can be identical to other mudrock facies. Abandoned channels, however, may also almost completely fill up with peat (e.g. Törnqvist et al., 1993) and end up as coal plugs. Mudrock plugs need not always to be underlain by a sandstone body. Some anastomosing systems comprise channels that carry little sandy bedload (e.g. Page and Nanson, 1996; Gibling et al., 1998). When surrounded by overbank mud, mud-filled channels may be hard to recognize in the stratigraphic record. Ancient examples of predominantly mud-filled channels are the U-shaped mixed fills described by Eberth and Miall (1991). These were interpreted to represent crevasse channels that tapped the upper levels of flow of main channels, resulting in channel infilling by suspended load under generally low-energy conditions.

The mudrock facies contains important palaeoclimatic information indicated by its colours, organic content and palaeosols. Red and yellow colours, calcrete (nodules), desiccation cracks, and lack of organic matter are commonly considered indicative of an arid climate. In contrast, dark grey and green colours and abundant organic matter are suggestive of a humid climate. Caution must be used, however, in making these palaeoclimatic interpretations, as these properties may show considerable local variation, and they may partly represent the conditions of early diagenesis rather than the conditions of deposition. Miall (1996, pp. 437–442) gives an overview of the problems associated with palaeoclimatic interpretation of overbank deposits.

4.3.3. Coal facies

Excluding the coal incorporated in abandoned channel plugs, the coal facies usually occurs in seams, with blanket geometries. The seams commonly are laterally extensive and can be traced for up to kilometres. The coal seams are usually thin, and intercalated mudrock beds frequently occur. In general, thickness ranges up to 2 m. In systems where the mudrock facies is virtually absent (e.g. Cairncross et al., 1988), the coal facies strongly dominates the anastomosing river lithofacies. In such cases, the seam thickness may be up to 8 m (Le Blanc Smith and Eriksson, 1979). Coal blankets are most frequently encased in mudrock, but scoured upper or lateral contacts with ribbon sandstone bodies are also common.

The coal facies is interpreted to represent the mire depositional environment. Coal is not present in all ancient anastomosing river systems. Absence or rarity of coal has been attributed to high clastic influx (Nadon, 1994) or arid climatic setting (Rust and Legun, 1983; Kumar and Tandon, 1985; Eberth and Miall, 1991). The thickness of coal seams is strongly influenced by compaction. They may represent significant quantities of peat. For example, the estimated proportions of pre-compacted and post-compacted coal and carbonaceous mudstones differ from 40% to 11%, respectively, in sections studied by Kirschbaum and McCabe (1992). McCabe (1984, p. 20) cited peat-to-coal compaction ratios between 1.4:1 and 30:1.

4.4. The alluvial architecture of interpreted ancient anastomosing river systems

In this section, three aspects of anastomosing river alluvial architecture will be discussed: (1) the proportion of overbank deposits relative to channel deposits, (2) the lateral connectedness of the channel sandstone bodies and (3) the geometry (width/thickness ratio) of the channel sandstone bodies. These properties are of considerable economic significance. In Table 3, data about these aspects for sixteen interpreted ancient and subrecent anastomosing river systems are summarized.

4.4.1. Proportion of overbank deposits

Subsurface data from modern anastomosing rivers suggest that large amounts of overbank deposits are preserved (Smith and Smith, 1980; Smith, 1983, 1986). The proportion of overbank deposits preserved in the stratigraphic record is controlled by several interrelated variables, most importantly: (1) lateral mobility of the fluvial channels; (2) channel density; and (3) floodplain aggradation rate. Since many modern anastomosing rivers have straight, laterally stable channels, overbank deposits tend to escape lateral erosion. Rust (1981) believed that channel density in arid anastomosing river systems is significantly lower than in humid anastomosing river systems. In this respect he quoted values of 3% of the floodplain occupied by active channels on the arid Cooper Creek floodplain as opposed to 20% for the humid Alexandra River. These values, however, are strongly determined by large differences in basin width and probably are not representative for arid and humid anastomosing rivers in general. Two-dimensional (cross-valley) simulation studies (e.g. Bridge and Leeder, 1979; Bridge and Mackey, 1993) suggested a positive correlation between aggradation rate and preservation of overbank deposits, which could be especially relevant for anastomosing river systems, since a number of them show high aggradation rates (Table 2). The validity of this correlation however, was questioned by Bryant et al. (1995). They found experimental evidence for a rise in avulsion frequency with sedimentation rate, which decreases the proportion of overbank deposits by increasing the number of channel sandstone bodies. Mackey and Bridge (1995) and Heller and Paola (1996) used three-dimensional simulation models to further explore the complex relationship between floodplain aggradation rate and the proportion of overbank deposits preserved. Long-term coexistence of channels, however, is not considered in these models.

The ancient river systems (Table 3) all show a high proportion of overbank deposits, which is in agreement with data from the modern record. Where modern and ancient environments are compared, correction should be made for compaction of muds and organics. Compaction differences may explain why the proportion of overbank deposits in the Holocene Betuwe Formation (The Netherlands) is higher than in the ancient examples of Table 3.

4.4.2. Lateral connectedness of channel sandstone bodies

If preserved in the stratigraphic record, sandy channel-fills of anastomosing rivers will mainly occur as networks encased in overbank muds. For most examples in Table 3, lateral connectedness of channel sandstone bodies was reported. However, not every network of sandstone bodies in the stratigraphic record is of anastomosing river origin, since contacts between sandstone bodies can be erosive and do not necessarily originate from confluence or bifurcation of contemporaneously active channels (see also Schumm et al., 1996).

The degree of connectedness of the individual sandstone bodies is an important variable in reservoir characterization. Essential is planform information on the sandstone bodies. In some cases, planform exposures are available in which channel sandstone body connectedness can be readily observed (e.g. Eberth and Miall, 1991). In other cases, tight core control is needed, which may be aided in subrecent systems by geomorphological evidence for the subsurface patterns (Bakker et al., 1989; Törnqvist, 1993a; Berendsen et al., 1994). In the deeper subsurface, pressure data can be used to test fluid connection between reservoir channel sand bodies (e.g. Putnam, 1993; Wightman et al., 1987). Sometimes, connectedness is rather inferred from the observation of more channel sandstone bodies at exactly the same stratigraphic level in cross-sections. Nadon (1994) and Kraus and Wells (1999), for example, observed sandstone 'wings', attached to the top of channel bodies, of which the beds could be traced from one sandstone body to an adjacent sandstone body. Kraus and Wells (1999), however, also had planform data suggesting connectedness.

It is hard to prove whether several connected sandstone bodies represent contemporaneously active channels. In the case of organic-rich Holocene to Late Pleistocene deposits, ^{14}C-dating of the period of activity of the individual branches may provide conclusive evidence (e.g. Törnqvist, 1993b, 1994). However, in most cases, coexistence of channels can only be assumed on the basis of stratigraphic arguments (e.g. Currie et al., 1991; Bakker et al., 1989; Flores and Hanley, 1984).

4.4.3. Width / thickness ratio of channel sandstone bodies

The importance of the shape of channel deposits as an indicator of former lateral channel stability was stressed by Collinson (1978). Friend et al. (1979) and Friend (1983) used the width/thickness ratio of channel-fill bodies to infer former channel behaviour. Bodies with width/thickness ratios < 15 were called ribbons and thought to reflect fixed channels subject to switching by avulsion. Bodies with width/thickness ratios > 15 were called sheets and were viewed as a product of lateral migration of a channel. Nadon (1994) proposed a width/thickness ratio of 30 as an upper limit of ribbons. Although both the values of 15 and 30 are arbitrary, the concept of reconstructing channel behaviour from the geometry of the channel-fill bodies is useful. Naturally, it first should be ascertained that the sand body really is the product of channelized flow (e.g. by longitudinal dimension). Sandstone sheets may, for example, also represent crevasse splays deposited by sheetfloods.

The width/thickness ratio of a channel-fill body is determined by: (1) the width/depth ratio of the original channel; (2) a lateral migration component; and (3) a vertical aggradation component (Fig. 16). From Table 3, it appears that the width/thickness ratios of the ancient and subrecent channel sandstone bodies vary widely and that many of them are not ribbons in the terminology of Friend (1983) (i.e. $w/t < 15$). Comparison with the width/depth ratios of modern anastomosing channels (Table 2) shows that on average the width/thickness ratio of the channel sandstone bodies is significantly greater than the width/depth ratios of modern anastomosing channels. There are three possible explanations: (1) sandstone sheets, representing crevasse splays or levees laterally connected to channel sandstone bodies, were misidentified as channel-fill deposits, leading to overestimation of the width of the channel body; (2) the width/depth ratio of the palaeochannels was greater than those of modern anastomosing channels; or (3) the sandstone ribbons were partly formed by lateral accretion.

The first explanation particularly applies to situations where reconstructions are based on geophysical or limited borehole data. In these cases, wide spacing of logs may also lead to apparent lateral amalgamation of separate channel sandstone bodies (e.g. Wightman et al., 1987). The second and the third explanation may in fact both be applicable at the same time, since actively meandering channels tend to have higher width/depth ratios than laterally stable channels. Page and Nanson (1996) reported laterally extensive sandstone sheets [w/t up to 1000 (Table 3)] forming the base of Late Quaternary channel-fill sequences, which are believed to represent, at least partly, an anastomosing system. The sheets are relatively thin, since the upper parts of the channel-fills consist of mud. The width of the sheets is obviously due to lateral channel migration, as testified by meander scars and scroll-patterned floodplains visible on air photographs. Lateral accretion units were also recognized in some of the ancient channel sandstone bodies described by Rust and Legun (1983), Rust et al. (1984), Nadon (1994) and Kirschbaum and McCabe (1992). The on average relatively great width/thickness ratio of ancient anastomosing channel sandstone bodies (Table 3) renders it unlikely that the ancient channels were generally keeping pace with strong vertical floodplain aggradation (second picture of Fig. 16), as was suggested for modern anastomosing channels by Smith and Smith (1980) (see also Fig. 11). In that case, one would expect much lower width/thickness ratios for most of the examples in Table 3.

4.5. Evaluation

Only a limited number of ancient stratigraphic examples has been interpreted as anastomosing in origin. Since anastomosis typically occurs in the lower reaches of rivers in aggrading basinal settings where preservation potential tends to be high, one

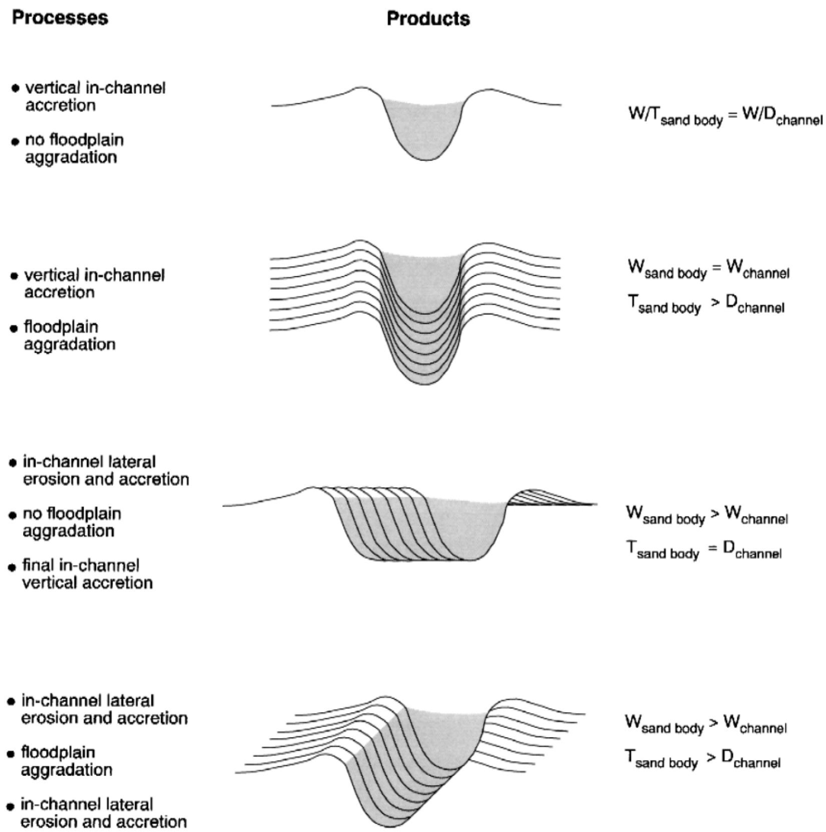


Fig. 16. Cross-sections showing channel geometry, lateral migration and vertical aggradation determining the width/thickness ratio of a sandstone body.

would expect ancient anastomosing river systems to be relatively abundant in the stratigraphic record. I feel that probably many examples were not identified as ancient anastomosing river systems, mainly because of: (1) the restricted sedimentological database from modern anastomosing environments; (2) the relatively large scale of anastomosing rivers as a floodplain-wide fluvial form; and (3) the difficulty of proving coexistence of multiple channels in ancient examples.

It must be realized that most of what we know about the sedimentary facies of anastomosing rivers is based on a limited number of facies descriptions of modern anastomosing rivers. These modern rivers represent a dataset that is still strongly biased towards small to medium-scale anastomosing rivers in humid climatic settings. Although gradually more sedimentological information about other kinds of modern anastomosing rivers becomes available, additional case studies are still urgently needed for comparison with the stratigraphic record.

Anastomosing river systems are relatively large-scale geomorphological phenomena. Applying the term ‘anastomosing’ to a certain facies association in an ancient rock unit implies that the palaeogeomorphology of the river system can be inferred. Problems arising from the application of geomorphological classifications to ancient fluvial sediments were discussed (among others) by Friend (1983) and Miall (1985). As exposure is limited and especially planform information on ancient river systems is generally scarce, conclusions on palaeoriver morphology usually can only be drawn at the level of individual river branches.

The problem of limited chronological control of ancient systems, and therefore the inability of proving coexisting of channels, will remain in the near future. Presently, late Quaternary systems, within the range of ^{14}C-dating (50,000 years), offer by far the best opportunities to prove former anastomosing systems, and to study their long-term development and sedimentary sequences, within a detailed timeframe (e.g. Makaske, 1998; Morozova and Smith, 1999). Since preserved floodplain organics are required, humid fluvial systems are much more suitable than arid systems. In the latter environment, thermoluminescence dating (TL) of fluvial sediments may provide an alternative (e.g. Page and Nanson, 1996; Page et al., 1996). An advantage is that TL has the ability to date to 300,000 years; however, the level of precision of TL dates is generally too low to prove coexistence of palaeochannels.

Besides these identification issues, another important problem is that the development of an anastomosing rivers facies model was hindered by the lack of a sound conceptual framework with regard to the definition and classification of anastomosing rivers. In current definitions, anastomosis (in the sense of multiple channels) and lateral stability of channels are often inseparably coupled. As shown earlier in this paper, these two properties are driven by different process complexes (e.g. Fig. 9). As a result, not all laterally stable channels are parts of multi-channel systems (e.g. Nanson and Croke, 1992, p. 477), and on the other hand, not every anastomosing, multi-channel system needs to consist of laterally stable channels (see Section 2.3). However, in comprehensive studies on fluvial styles and facies models (e.g. Miall, 1985, 1992), the single-channel straight river has been neglected. As a result, ribbon sandstones are often automatically taken to represent anastomosing rivers.

A ‘straight river facies model’ needs to be defined as a logical extension of the suite of braided and meandering river facies models in the low-energy domain. These models, although including overbank deposits, are mainly based on the lithofacies of channel sediments and can be applied at the channel scale. In addition, the anastomosing river model should be considered as a model for a large-scale fluvial depositional system. Reineck and Singh (1980, pp. 305–306) for example, distinguish in this respect three ‘fluvial associations’ in which river deposits occur: (1) the alluvial fan association, (2) the floodplain association and (3) the coastal plain–delta association. Their coastal plain–delta association in fact represents the anastomosing river environment. An important step forward would be to implement anastomosis (and systematic variations in the number of coexisting channels) in simulation models for fluvial architecture (e.g. Mackey and Bridge, 1995) and sequence stratigraphic models for nonmarine strata (e.g. Wright and Mariott, 1993; Shanley and McCabe, 1993).

At present, there is no consensus on the question whether the anastomosing fluvial environment includes the fluviodeltaic environment. There is a tendency to consider the anastomosing river environment as a continental counterpart of the fluviodeltaic environment, but some workers apply the term anastomosing to subrecent and modern channels in deltaic environments (Peng, 1990; King and Martini, 1984), especially in the Rhine–Meuse delta in the Netherlands (Törnqvist, 1993a; Weerts and Bierkens, 1993; Bosch and Kok, 1994; Weerts, 1996; De Groot and De Gans, 1996; Makaske, 1998). In my view, coexistence of channels in deltaic environments is not fundamentally different in processes and products from anastomosis in continental settings. In both situations, multiple channels result from avulsions, with the only difference that avulsions in near-coastal settings may be caused or triggered by marine processes (e.g. silting up of river mouths by longshore currents, river flooding due to set up of sea level caused by storm and/or spring tide). Although fluviodeltaic lithofacies may differ in detail from continental anastomosing river lithofacies [e.g. muddrapes in fluviodeltaic channel deposits (including IHS) recording tidal or marine influence (Smith, 1987; Thomas et al. 1987)], studies of Holocene fluviodeltaic sequences demonstrate that alluvial architecture can be very similar to that of inland anastomosing counterparts (e.g. Törnqvist et al., 1993; Makaske, 1998).

Application of concepts derived from anastomosing rivers to fluviodeltaic environments may lead to refinement of sequence stratigraphic models for nonmarine strata (e.g. Wright and Mariott, 1993; Shanley and McCabe, 1993). In sequence stratigraphic studies, sand body width/thickness ratio is often interpreted to be inversely related to floodplain sedimentation rate (e.g. Shanley and McCabe, 1991; Mjøs and Prestholm, 1993; Aitken and Flint, 1995). A similar relationship was found by Törnqvist (1993a,b) for the Holocene sequence of the fluvial Rhine–Meuse delta. Floodplain sedimentation rates in near-coastal fluvial settings are principally driven by relative sea-level rise. A rapid rise in base level (sea level) causes a prolonged reduction of channel gradients, favouring low-energy, laterally stable channels that will be preserved as sand bodies with a low width/thickness ratio. It is generally accepted that fluvial systems respond to changes in external conditions (including base-level changes) by changes in channel morphology (e.g. Schumm, 1993). However, evidence from the Rhine–Meuse delta suggests that near-coastal fluvial systems may also respond to base-level rise by changing the number of coexistent channels (Törnqvist, 1994; Makaske, 1998, pp. 226–229). Starting from a positive relationship between base-level rise, aggradation rate and avulsion frequency, it is reasonable to suppose that rapid sea-level rise makes the number of coexistent delta distributaries increase by frequent avulsion (Fig. 9). Since the same amount of water has to be distributed over an increasing number of channels, stream power for individual channels will inevitably decrease, resulting in an increase in lateral channel stability and eventually a decrease in sand body width/thickness ratio.

In sequence stratigraphic terms, it can be stated that multiple coexistent, laterally stable channels may typify transgressive systems tracts (TSTs); i.e. nearshore depositional systems associated with rapidly rising sea level. Some authors, however, argue that initially rapid sea-level rise does not create much accommodation space in upper nonmarine parts of deltas (Shanley and McCabe, 1993). Only when the coastline has shifted far inland, relative sea-level rise is ‘felt’ in this area. This may be near sea-level highstand, rather than during rapid transgression. In this case, multiple coexistent channels can be expected to typify the early highstand systems tract (HST) instead of the TST. Another matter is the preservation potential of HST and TST deposits. If basin subsidence is slow, for example along passive continental margins, a large part of the TST-deposits may be eroded during the next sea-level lowstand. In more rapidly subsiding settings, for example foreland basins, at least TST-deposits have a much higher chance of preservation.

Although sequence stratigraphy primarily focuses on the effect of eustatic sea-level changes on near-coastal depositional systems, important systematic changes in base level (related to climatic cycles) may also occur in intracratonic nonmarine settings. Lake-levels in semi-arid or arid environments rapidly rise and fall in response to arid-humid climatic cycles and lake-feeding fluvial systems may respond by changing morphology. In the Inland Delta of the Niger River in central Mali, late Quaternary arid periods resulted in degradation of the channel network, by in-channel aeolian sedimentation and dissection of the levees by gullies. During transition from arid to humid the fluvial network could not accommodate the rising discharge that resulted in avulsions and coexistence of multiple channels. At the same time, local base level rose rapidly due to formation of large lakes downstream, partly because large cross-valley longitudinal dunes, erected during the preceding arid period, obstructed river flow (Tricart, 1959, 1965; Gallais, 1967; Makaske, 1998). In such arid intracratonic settings, sedimentation rates tend to be slow, while climatic changes are relatively frequent (or at least were during the Late Quaternary). This inhibits thick sequences of anastomosing river deposits formed under constant climatic conditions. Nevertheless, anastomosing river deposits are likely to make up an important part of the cyclic basin-fill.

5. Conclusions

In presently popular definitions of anastomosing rivers, lateral stability of channels is presumed along with their multi-channel character. However, the coupling of channel-scale properties and multiple-channel character in the same definition seems conceptually wrong. Besides, it is unpractical in sedimentological applications. Therefore, I propose the following redefinitions: (1) at the channel-belt scale, the term ‘straight’ should be used to describe laterally stable channels having a sinuosity index lower than 1.3; (2) at a larger scale, rivers should be called anastomosing if *a river is composed of two or more interconnected channels that enclose floodbasins*. In this paper, I started from these definitions. The conclusions reached concerning the genesis of anastomosing rivers are listed below.

(1) Anastomosing rivers are formed by avulsions, i.e., flow diversions that cause the formation of new channels on the floodplain. As a product of avulsion, anastomosing rivers essentially form in two ways: (a) by formation of bypasses, while bypassed older channel-belt segments remain active for some period; and (b) by splitting of the diverted avulsive flow, leading to contemporaneous scour of multiple channels on the floodplain.

(2) Avulsions are primarily driven by aggradation of the channel belt and/or loss of channel capacity by in-channel deposition. Both processes are favoured by a low floodplain gradient. Of secondary importance are a number of avulsion triggers such as extreme floods, log and ice jams, and in-channel aeolian dunes. Although some of these triggers are associated with a specific climate, the occurrence of anastomosis is not.

(3) Long-lived anastomosis is caused by frequent avulsions and/or slow abandonment of old channels. With respect to avulsion frequency, anastomosing rivers range from highly dynamic to semi-static. In semi-static systems, anastomosis seems to result mainly from extremely slow infilling of old channels after infrequent formation of new channels. In more dynamic systems, anastomosis rather results from the frequent formation of new channels, while old channels remain active for some time.

(4) A rapid rise of base level is conductive to anastomosis, but is not a necessary condition. Some extensive anastomosing river systems apparently exist in equilibrium with stable external conditions.

(5) The often-observed high lateral stability of individual channels in anastomosing rivers is caused by low stream power in combination with resistant banks. Both conditions are strongly related to a low floodplain gradient.

With respect to genesis and lifetime, four basic types of anastomosing rivers can be identified: (1) short-lived anastomosis within an avulsion belt; (2) short-lived, transitional anastomosis during a single avulsion, due to temporary coexistence of an older trunk channel and a new avulsion channel; (3) long-lived, highly dynamic anastomosing systems, constantly rejuvenated by frequent avulsions caused by allogenic controls; and (4) long-lived, semi-static anastomosing systems, which seem in equilibrium with stable external conditions. Since these four types are morphologically quite similar, anastomosing rivers can be considered an example of equifinality, i.e., different combinations of processes or causes produce a similar form.

Since anastomosis typically occurs in the lower reaches of rivers in (rapidly) aggrading basinal settings where preservation potential tends to be high, ancient anastomosing river systems are expected to be relatively abundant in the stratigraphic record. Below, the main characteristics of anastomosing river deposits will be given.

(1) The alluvial architecture is characterized by a large proportion of overbank deposits (probably 50% to 90%) which encase laterally connected channel sandstone bodies.

(2) Laterally extensive, thick lenses of lithologically heterogeneous, fine-grained avulsion deposits can be an important element of the overbank deposits of anastomosing rivers. These deposits may also fully surround anastomosing channel sandstones. Typically, they also encase sheet-like crevasse splay sandstones.

(3) The geometry of anastomosing channel sandstone bodies is frequently characterized by a ribbon shape and a flat top.

(4) Channel deposits predominantly consist of sandstone which may fine upward, but also can be quite homogeneous. In the latter case, the sandstone may pass abruptly into overlying mudrock.

(5) Crevasse splay deposits and thick natural levee deposits are common elements.

(6) Lacustrine deposits and coal commonly occur in association with anastomosing river overbank deposits (in arid settings, lacustrine deposits and coal may be absent).

It should be noted that none of these characteristics is unique to anastomosing river deposits. Application of the geomorphological term 'anastomosing' to ancient fluvial systems requires careful and often large-scale palaeogeographical reconstruction. In practice, subrecent anastomosing river environments offer by far the best opportunities to realize this. In ancient rocks, geomorphological interpretation of fluvial facies will often be restricted to a classification of individual palaeochannels as being braided, meandering or straight, and sometimes even a less precise reconstruction will be the best attainable. In these cases, a purely descriptive geometric classification of ribbon and sheet sandstone bodies is an alternative.

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