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Preface

Papers in this IAS Special Publication are derived from oral and poster presentations at the 7th International Conference on Fluvial Sedimentology (ICFS), held in Lincoln, Nebraska (USA), 6–10 August 2001. The ICFS series was initiated in Calgary, Alberta in 1977, has been held every four years, and has become a staple within the international fluvial sedimentology community. The 7th ICFS was attended by 289 professionals and students from 28 countries, who represented universities, government institutions and private enterprise. The next meeting in this series, the 8th ICFS, will be held in 2005 at Delft, The Netherlands, and will be hosted by Delft University of Technology (http://www.8thfluvconf.tudelft.nl/).

The 7th ICFS was hosted by the Department of Geosciences of the University of Nebraska-Lincoln, and, like its predecessors, operated without an umbrella provided by formal affiliation with professional scientific organizations. Indeed, the 7th ICFS could not have taken place without the generous sponsorship and logistical support provided by the University of Nebraska, the hard work contributed by many University of Nebraska faculty and students, the efforts of the many conference field trip leaders, and the financial assistance provided by the International Association of Sedimentologists, Society for Sedimentary Geology, American Association of Petroleum Geologists, Conoco Inc., ExxonMobil Upstream Research Co., Phillips Petroleum Company, Schlumberger Reservoir Technologies and STATOIL.

The 7th ICFS included four days of technical sessions, with 175 oral presentations and 60 posters, plus nine pre-, post- and mid-conference field trips. Conference themes reflected the topical and geographical diversity of exciting research being conducted by fluvial sedimentologists at the beginning of the twenty-first century, and included the following:

1 General topical sessions
   • flow, sediment transport and bedform dynamics
   • fluvial channel systems—modern and ancient
   • fluvial overbank systems—modern and ancient
   • sequence stratigraphy of alluvial successions
   • fluvial systems and economic resources
   • river management

2 Special interest symposia
   • alluvial architecture
   • dryland rivers—process and products
   • deposits in mud-dominated rivers
   • alluvial and tectonic system interactions
   • fluvial system response to climate change through time
   • alluvial responses to accommodation changes
   • response of near-coastal fluvial systems to sea-level change
   • fluvial reservoirs
   • fluvial–estuarine transitions
   • the Late Quaternary Rhine–Meuse system

A similar topical and geographical diversity is reflected in the 29 papers included in this Special Publication. In the first group, one set of papers focuses on flow, sediment transport and bedform dynamics. J. Best presents a series of laboratory and field observations on dune-related macroturbulence. I. Fuller and others quantify reach-scale sediment transfers in the River Coquet, England. M. Kleinhans summarizes results of flume experiments coupled with empirical data from the Rhine to discuss dune-phase bedload transport and the importance of sorting processes. S. Leclair and A. Blom present results of flume experiments designed to decipher controls on the probability...
distribution of bed-surface elevations, and the structure and texture of the associated deposits, under dune-forming conditions. C. Marti and P. Bezzola present early results of numerical and physical modelling of Alpine streams, which are designed to assist redevelopment of more natural braided patterns in rivers that have been artificially narrowed as a result of river training activities. Last, P. Villard and others discuss the measurement of bedload in sand-bed channels using an acoustic Doppler profiler, and the merits of this technique relative to traditional mechanical samplers.

The second set within the first group focuses on the characteristics of modern fluvial landforms, environments and systems. D. Abbado and others describe the role of high floodplain aggradation rates in promoting anastomosis along a reach of the Columbia River in British Columbia. A. Archer provides a very useful and extensive review of the state of knowledge on Amazonian depositional systems. C. Krapf and others describe the processes, characteristics and importance of fluvial–aerial interactions for the Koigab Fan in north-west Namibia. G. Sambrook Smith and others discuss the spatial scale invariance of bar shapes and scour depths in modern braided rivers, as well as the difficulties of applying scale invariant concepts to older deposits owing to the importance of temporal evolution and rates of migration of bar forms. P. Siiro and others use laser diffraction analysis to compare the grain-size distributions of Cretaceous and the Miocene epicontinental embayment/seaway systems in South and North America, so as to unravel the formation of sand–mud couplets within tidally influenced inclined heterolithic strata. Finally, R. Sinha and others describe the sedimentological characteristics and avulsion history within an anabranching reach of the Bagmati River, India, which flows from the Himalayan foothills into the rapidly subsiding foreland.

A short second group focuses on physical analogue and numerical modelling. F. Ethridge and others provide an overview of a generation of experimental studies at Colorado State University on the morphological and stratigraphical effects of base-level change. This is followed by N. Strong and others who present a new approach for the quantification of downstream changes in alluvial architecture based on mass-balance considerations.

The third group includes papers that address the responses of Quaternary fluvial systems to climate change, active tectonics, and/or sea-level change. A. Amorosi and M. Colalongo discuss alluvial and coeval nearshore marine successions of the Po River Plain, Italy, and consider some implications for sequence-stratigraphy models. M. Benvenuti and others describe depositional processes, facies and the latest Pleistocene to modern evolution of discontinuous ephemeral streams of the main Ethiopian rift. K. Cohen and others discuss how detailed studies of fluvial–deltaic deposits of the Rhine–Meuse delta, The Netherlands, record differential subsidence. C. Fielding and others describe the response of the ancestral Burdekin River, north-east Australia, to sea-level fall, as it cut across the Great Barrier Reef Shelf. M. Jain and others document the Quaternary stratigraphical development of the Luni River system, in the Thar Desert of western India, and the influences of tectonic activity and climate change over a variety of time-scales. Finally, M. Mancini and G. Cavinato summarize the Plio-Pleistocene evolution of the Tiber River system, central Italy, in response to extensional tectonics, volcanism and climate change.

The final group of papers addresses a variety of topics based on studies of pre-Quaternary fluvial systems. The first paper by P. Friend and W.B. Dade presents a model for transport modes and grain-size patterns in fluvial basins. W. Galloway summarizes his conference keynote address, and in doing so provides an overview of Cenozoic North American drainage basin evolution, as recorded in the northern Gulf of Mexico basin, offshore Texas and Louisiana, USA. S. Greb and R. Martino describe fluvial–estuarine transitions in the Lower Pennsylvanian of the Central Appalachian Basin, eastern USA. R.M. Joeckel and others present a detailed summary of fluvial to estuarine architecture and palaeogeography of the Cretaceous Dakota Formation from eastern Nebraska, USA. K. Keogh illustrates the utility of thre-dimensional models of alluvial architecture, using the Westphalian A Silkstone Rock, Pennine Basin, UK as a case study. M. Lumsdon and A.G. Plint discuss how changes in the rate of generation
of accommodation affects alluvial style in the Upper Cretaceous Dunvegan Formation, north-east British Columbia, Canada. S. Marriott and others discuss fining upward sequences in a mudrock dominated succession of the Lower Old Red Sandstone of South Wales, UK, and suggest an environment of deposition similar to that of the Channel Country in central Australia, where bedload often consists of sand-sized mud aggregates. R.S. Root and others use a data set from the Tarbat–Ipundu Field in south-west Queensland, Australia, to demonstrate how sequence stratigraphy can be applied at the hydrocarbon reservoir scale. Finally, K. Yagishita and O. Takano describe floodplain strata and their sequence-stratigraphy significance within braid delta deposits of the Oligocene Minato Formation, north-east Japan.


MICHAEL BLUM
Baton Rouge, Louisiana, USA

SUSAN MARRIOTT
Bristol, United Kingdom

SUZANNE LECLAIR
New Orleans, Louisiana, USA
Fluvial processes and forms
INTRODUCTION

Anastomosed rivers consist of two or more interconnected, coexisting channels that typically enclose concave-upwards floodbasins. The channels are usually straight or slightly sinuous, but braided and meandering patterns are also known. Thus, anastomosed rivers are different from braided rivers because the latter contain multiple thalwegs enclosing convex bars within a single channel (Makaske, 2001) whereas anastomosis defines a network of anabranched channels. Although the geomorphological characteristics of anastomosed rivers have been recognized and described (Smith & Putnam, 1980; Smith & Smith, 1980; Rust, 1981; Smith, 1983, 1986; Nanson et al., 1986; Schumann, 1989; Miller, 1991; Knighton & Nanson, 1993; Smith et al., 1997, 1998; Makaske 1998, 2001), the origin of anastomosis is still an unresolved matter (Nanson & Huang, 1999; Makaske 1998, 2001). Indeed, Makaske (1998) argued that understanding the causes of anastomosis is one of the major challenges in current fluvial research, and Nanson & Huang (1999) asserted that anabranching rivers (including anastomosed rivers) ‘remain the last major category of alluvial systems to be described and explained’.

Origin of anastomosis in the upper Columbia River, British Columbia, Canada

DIMITRI ABBADO*, RUDY SLINGERLAND*†, and NORMAN D. SMITH†

*Department of Geosciences, Pennsylvania State University, 503 Deike Building, University Park, PA 16802, USA (Email: sling@geosc.psu.edu); and
†Department of Geosciences, University of Nebraska, 214 Bessey Hall, PO Box 880340, Lincoln NE 68588, USA

ABSTRACT

To understand the origin of anastomosis on the Columbia River between Spillimacheen and Golden, British Columbia, Canada, a geomorphological and sedimentological survey was undertaken during the summer flood of 2000. On the basis of these observations, the study reach can be divided into two sub-reaches: a highly anastomosed section with three to five channels, and a weakly anastomosed section with one to two channels. The highly anastomosed reach occurs immediately downstream from the Spillimacheen tributary and is characterized by a higher channel slope, a higher number of crevasse splays, a larger combined crevasse splay area, a wider valley and a coarser bedload. Higher rates of floodplain aggradation in the highly anastomosed reach are suggested by modern sediment budgets and radiocarbon dates. These geomorphological and sedimentary associations are consistent with the hypothesis that anastomosis of the Columbia River is maintained by a dynamic equilibrium between the rates of channel creation and channel abandonment. Rising base-level, fine bedload and low bed-slope are not necessary immediate conditions for anastomosis of the Columbia River.

INTRODUCTION

Anastomosed rivers consist of two or more interconnected, coexisting channels that typically enclose concave-upwards floodbasins. The channels are usually straight or slightly sinuous, but braided and meandering patterns are also known. Thus, anastomosed rivers are different from braided rivers because the latter contain multiple thalwegs enclosing convex bars within a single channel (Makaske, 2001) whereas anastomosis defines a network of anabranched channels. Although the geomorphological characteristics of anastomosed rivers have been recognized and described (Smith & Putnam, 1980; Smith & Smith, 1980; Rust, 1981; Smith, 1983, 1986; Nanson et al., 1986; Schumann, 1989; Miller, 1991; Knighton & Nanson, 1993; Smith et al., 1997, 1998; Makaske 1998, 2001), the origin of anastomosis is still an unresolved matter (Nanson & Huang, 1999; Makaske 1998, 2001). Indeed, Makaske (1998) argued that understanding the causes of anastomosis is one of the major challenges in current fluvial research, and Nanson & Huang (1999) asserted that anabranching rivers (including anastomosed rivers) ‘remain the last major category of alluvial systems to be described and explained’.

1Corresponding author.
Three hypotheses exist for the origin of anastomosis. In the first, anastomosis is a consequence of frequent avulsions and slow abandonment of earlier channels (see e.g. Makaske (2001) and references therein). According to this point of view, the fluvial system exists in a perpetual transition state consisting of multiple coexisting channels. Anastomosis is thus not a ‘graded’ state, but rather a by-product of the competition between channel creation and abandonment. Makaske (2001), for example, defined an anastomosed system as the product of a dynamic balance between frequent avulsions that create multiple channels and slow channel abandonment. According to Makaske, the immediate causes of the frequent avulsions are a rise in base-level, subsidence (Smith, 1983), and high rates of aggradation, whether of the channel belt or within the channel. The immediate cause of slow abandonment is conjectured by Makaske (2001) to be low stream power, although few data exist.

In the second hypothesis, anabranching and anastomosed rivers are thought to be an equilibrium form where channels are adjusted in geometry and hydraulic friction to just transmit the imposed water and sediment discharges. In cases where gradient cannot easily be increased to carry a larger sediment load, Nanson & Knighton (1996) and Nanson & Huang (1999) proposed that a shift from single to multiple channels leads to an increase in sediment transport rate per unit water discharge. Thus, like changes in slope and channel form, anastomosis is conjectured to be another mechanism whereby a fluvial system can maintain grade. Makaske (1998) challenged this idea, however, arguing that the multichannel state of the upper Columbia River cannot be taken as a response of the system to maximize water and sediment throughput because, in spite of its anastomosed morphology, the bulk of its water and sediment moves through a single channel.

The third hypothesis was put forward by Galay et al. (1984) from a study of the Columbia River. They postulated that ponding behind alluvial fans led to the formation of large lakes in the upper Columbia Valley. The lakes gradually were filled by river-dominated ‘bird’s-foot’ deltas of which the present anastomosed river system is a final stage. This type is thought to result from contemporaneous filling of shallow lakes and scour of multiple channels in avulsion belts, so the anastomosis should be transitional and short-lived. A subsequent palaeoenvironmental reconstruction of Columbia River deposits (Makaske, 1998) has shown that its anastomosed channels are long-lived and not the result of delta growth into shallow lakes. Therefore this hypothesis will not be considered further here.

The purpose of this paper is to describe the hydraulic and morphological properties of the anastomosed reach of the upper Columbia River in British Columbia, Canada, in order to assess the origin of its anastomosis. The Columbia River near Golden, British Columbia is an appropriate field site, being one of the best-known examples of anastomosis (Locking, 1983; Smith, 1983; Makaske, 1998, 2001; Adams, 1999; Machusick, 2000). Furthermore, hydrological and photographic records are available starting from the first half of the 1900s.

LOCATION AND GEOMORPHOLOGY OF THE STUDY AREA

The study reach is a section of the upper Columbia River near Golden, British Columbia, Canada (Fig. 1). The Columbia River starts at Columbia Lake in southern British Columbia, approximately 80 km south-east of the study reach, and flows north-north-west in a 1–2-km-wide valley for a distance of 160 km along the Rocky Mountain Trench before turning west and south-west. It consists of a single channel between Columbia Lake and the town of Radium, an anastomosed reach between Radium and a kilometre upstream of Golden, and a braided reach at Golden where it flows across the alluvial fan of a tributary, the Kicking Horse River. Anastomosis is particularly evident downstream of Spillimacheen, and this report concentrates on the 55-km reach between Spillimacheen and Golden. Access is provided by Route 95 along the north-east side of the valley, by bridges at Nicholson, Parson and Spillimacheen, and by a railway right-of-way. The area lies within the Cassiar–Columbia Mountain physiographic region and in the Interior Douglas-Fir biogeoclimatic zone (Farley, 1979). Mean annual precipitation varies between 40 and 50 cm yr\(^{-1}\), and mean daily temperature varies from \(-12\) to \(15^\circ\text{C}\) in January and July, respectively (Farley, 1979).
Anastomosis of the upper Columbia River, BC

Geomorphology and sedimentology of the study reach

In the study reach, the Columbia River consists of multiple, relatively stable channel belts containing low-sinuosity to straight, low-gradient, sand-bed channels. Levees and crevasse splay fringes of the channel belts bound floodbasins containing shallow wetlands and lakes. The channel belts show little lateral migration over their lifetimes, as indicated by the absence of scroll bars on the modern floodplain and by the near vertical accretion of channel facies as seen in cores (see e.g. Makaske, 1998, fig. 3.5). The channels are relatively straight, although smaller channels are slightly more sinuous. Thirty-seven tributaries enter along the reach, forming alluvial fans that narrow the valley and act as local sediment sources. The two largest tributaries are the Spillimacheen River (drainage basin of 1430 km²) and the Kicking Horse River (drainage basin of 1850 km²), which respectively define the upstream and downstream limits of the study reach. The Spillimacheen River catchment is a major sediment source for the study reach, contributing silt to fine gravel.

An important observation bearing on the origin of anastomosis is the number and location of channels and their evolution through time. Vibracores show that anastomosed channel deposits in the study reach are characteristically 5–15 m thick, narrow, interconnected stringers of sand (Smith, 1983) that contain sandy crevasse-splay fringes. These facies are stacked vertically, indicating that the channels occupy the same valley location for durations of up to approximately 3000 yr or maybe even longer (Smith, 1983; Makaske, 1998). Vertical aggradation rather than lateral accretion is the dominant sedimentation pattern, a conclusion also supported by the virtual absence of modern oxbow-lake and point-bar deposits. In one cross-valley stratigraphical section (Makaske, 1998), at least nine channels have existed over the past 3000 yr. Of these, six came into existence and three went extinct, indicating the long-term existence of the anastomosed pattern and the episodic nature of channel creation. There is also some indication that the longer lasting channels are wider than 30–50 m (Makaske, 1998), possibly because smaller channels can be occluded by log jams or have their gradient strongly diminished by beaver dams.

The Columbia River sediment load consists of 59 to 82% suspended material (Makaske, 1998), or if wash load is also considered, 89% (Locking, 1983). Locking’s sediment budget indicates that at the end of the anastomosed reach near Nicholson (6 km upstream of Golden) the supply of suspended load is much less than the transport capacity of the river. This decline in suspended load is evidence of a significant sediment sink in the anastomosed reach (Locking, 1983). Permanent sequestration of a portion of the bedload also occurs, with channel and crevasse splay storage roughly estimated by Smith to be, respectively, 66% (Smith, 1988) and 10–20% (D.G. Smith, as reported in Makaske, 1998).

Fig. 1 Location of the study area. The Columbia River flows north-north-west between the Kootenay Range of the Rocky Mountains and the Purcell Mountains. Soles Basin, selected as a typical floodplain of the anastomosing reach, lies immediately downstream of the Spillimacheen River, an important tributary.
Hydrology for the Columbia River at Nicholson (1947–present) and the Spillimacheen River near its mouth (1950–present) indicate that discharges for both are highly seasonal (Fig. 2). Minimum discharge for the Columbia occurs in February (average = 24 m³ s⁻¹), and maximum discharge occurs in June and July (average = 321 m³ s⁻¹), with overbank discharge of 45 days per year on average occurring almost every year (Locking, 1983). Our field observations were taken during the year 2000 flood, which was average in magnitude but short in duration and somewhat delayed owing to cold weather in June (Fig. 2b & d). The peak flow frequency distribution shows that the maximum peak of 351 m³ s⁻¹ registered at the Nicholson gauging station during the year 2000 occurs on average every 1.2 yr (1-yr flood).

LONGITUDINAL VARIATIONS IN ANASTOMOSIS AND RELATED FEATURES

To better understand the necessary conditions that give rise to anastomosis, the degree of anastomosis of the Columbia River was correlated with channel gradient, crevasse splay distribution, valley width, alluvial fan area, and channel-bed

Fig. 2 Discharge data for the rivers studied. (a) Discharge of the Columbia River at Nicholson 1947–2000. (b) Average monthly discharge of the Columbia over the interval 1947–1999 compared with year 2000 average monthly discharge. (c) Discharge of the Spillimacheen River at Spillimacheen 1950–2000. (d) Average monthly discharge of the Spillimacheen over the interval 1950–1999 compared with year 2000 average monthly discharge. Year 2000 flood was average in magnitude but of short duration and delayed owing to cold weather in June (Data from Environment Canada, 2001).
Anastomosis of the upper Columbia River, BC

grain size. These parameters were measured during the summer of 2000 or were observed on aerial photographs taken in 1996 at high stage, when the discharge measured at Nicholson was the third highest of the previous 10 yr. Given the hydrological data available from Environment Canada (formerly Water Survey of Canada) from 1947 to present, the 1996 peak discharge ($506 \text{ m}^3 \text{ s}^{-1}$) occurs on average every 3.3 yr (3-yr flood).

For our purposes, a channel belt is defined as active, in contrast with non-active, dry, or abandoned, if channels within it contain turbid water on the 1996 aerial photograph, thereby implying at least modest through-flow. Main channels are defined as those wider than 40 m; narrower channels are here termed secondary channels. Figure 3 shows a highly anastomosed section of the study reach where active/non-active channels and crevasse splays are indicated, as well as definition sketches of alluvial fan area, splay area and valley width.

Degree of anastomosis

To quantify the degree of anastomosis, the number of active channels at each of 29 valley cross-sections was counted. The number of channels, used here as a measure of anastomosis, varies from one to five with an average near two (Fig. 4a). On the basis of these differences, the study reach can be divided into an upper highly anastomosed reach (three to five channels), a weakly anastomosed reach (one to three channels), a single channel and a lower braided reach. The braided reach occurs as the Columbia River crosses the alluvial fan of the Kicking Horse River and will not be discussed further here.

Fig. 3 Morphological elements of the river system. (Top) 1998 aerial photograph of the Columbia River showing active and inactive channels and crevasse splays. (Bottom) Definition sketch showing how crevasse splay area, alluvial fan area, and valley width were computed. See Fig. 6 for location.
Longitudinal profile

Absolute water-surface elevations were measured at 34 points along the Columbia River using a Leica 500 differential global positioning system (GPS) with a subcentimetre vertical accuracy. The points were measured over the period 13–15 October 2000, between the bridge at Spillimacheen and the Kicking Horse River and corrected for a falling water level of 1 cm day\(^{-1}\). The water elevations (Fig. 4b) are plotted against along-channel distance rather than valley distance to avoid anomalies introduced by variable sinuosity or when the channel flows across the valley. The longitudinal profile is divisible into three sections. A relatively steep section from Spillimacheen to Castledale (\(S = 0.000215\)) is conjectured to reflect steepening of the Columbia River gradient as a result of sediment input from the Spillimacheen River. A steep section at Golden (\(S = 0.000442\)) arises as the Columbia River crosses the coarse-grained alluvial fan of the Kicking Horse River. Between Castledale and Golden is a more gentle central portion (\(S = 0.000068\)) in which the minor fans along the valley show little, if any, effect on channel gradient.

Fig. 4 Comparison of selected morphological parameters of the Columbia River. (a) Number of channels. (b) Elevation. (c) Number and area of splays. (d) Splay/valley-area ratio. (e) Valley width and alluvial fan area. (f) Mean grain size. See text for explanations.
Distribution of active crevasse splays

The study reach was divided into 29 cross-valley swaths, each 2 km wide, in which the numbers of active crevasse splays and their total surface areas were determined. A crevasse splay was considered to be active if turbid water was flowing across its surface in the 1996 aerial photographs. The number of active crevasse splays and total crevasse splay areas are both relatively high in the upper 12 km of the study reach (Fig. 4c). Figure 4d shows the percentage of the valley floor covered by active crevasse splays. There are 12 active crevasse splays in the upper 18 km and only six crevasse splays along the remaining reach. The area covered by active splays decreases monotonically with distance, the exception being an active avulsion site at kilometre 37. At this site, an ongoing avulsion blankets the whole floodplain with sediment, and small levees have formed since 1960 (Adams, 1999). The study reach therefore can be divided into two sections: an upstream reach with a high number of crevasse splays; and a downstream reach with a low number of crevasse splays.

Valley width

Valley width is potentially an important parameter in determining anastomosis because it defines the maximum available space in which channel belts can form. Variation in valley width is controlled by prograding alluvial fans from side tributaries. Measurements from aerial photographs of valley width and alluvial fan area (Fig. 4e) show little correlation with anastomosis.

Bed material grain size

Bed material was sampled during high stage on 24 June and 6 July 2000 from the mouth of the Spillimacheen River to 5 km upstream of the town of Nicholson. Twenty-five samples were collected along the main thalweg using a bucket sampler (height 15 cm, diameter 10 cm) with three replicates each to capture cross-channel variability. Mean grain size was computed using a self-constructed rapid sediment analyser to obtain a mean fall velocity that was then converted to mean particle diameter using the relationship of Dietrich (1982). Mean grain size shows considerable scatter (Fig. 4f), probably owing to variations in texture at the crest and troughs of dunes and the occasional introduction of coarse material from tributaries. Nevertheless, the bed material shows a statistically significant fining downstream in the study reach from 1.4–2.2 mm upstream to 0.5–1.1 mm downstream.

Interpretation

The above data indicate that the study reach of the Columbia River (excluding the braided section and single-channel reach) can be divided into two subreaches, a 17-km long, highly anastomosed reach with three to five channels starting immediately below the confluence with the Spillimacheen River, and a 38-km long, weakly anastomosed reach containing one to three channels. The highly anastomosed reach is characterized by a relatively steep channel slope, a higher number of crevasse splays, a higher total crevasse splay area, a higher splay-area/valley-area ratio and coarser bed material (Table 1). These are particularly interesting observations because previous studies have concluded that low gradients and fine grain sizes are necessary conditions for anastomosis (cf. Makaske, 2001). Previous studies also conjectured that rising base-level is a necessary immediate condition for anastomosis (Smith & Smith, 1980), but that is not supported by these data either.

The intensity of crevasse splay activity is interpreted to indicate that alluviation rates are higher in the upstream, highly anastomosed reach. Testing this interpretation with actual measured aggradation rates is difficult, however. The spatially averaged sedimentation rate during the 1982 flood cycle for the entire reach from Spillimacheen to Nicholson was 3.7 mm yr⁻¹ (Locking, 1983). This probably is an overestimation of the long-term average because it is based on the 1982 flood, which was well above average. A detailed sediment budget and geomorphological study of a floodbasin in the highly anastomosed reach (Fig. 1, Soles Basin) during the year 2000 flood (Abbado, 2001) shows that it is being actively filled at a rate of 2.2 mm yr⁻¹ by a combination of
short-lived crevasse splays, intrafloodbasin channels and settling of grains in temporary lakes. This estimate was obtained by simultaneously measuring the sediment flux into and out of the basin through crevasses and over levee tops during the 2000 flood. This must be considered a minimum because the flood of 2000 was shorter in duration than the average flood (Fig. 2b) and only suspended load was measured. In contrast, 16 km further down the study reach, an average aggradation rate of 1.7 mm yr\(^{-1}\) was obtained using a radiocarbon date of 4500 cal. yr BP from Scirpus lacustris nuts buried 7.9 m in a floodbasin (Makaske, 1998). Although the data are inconclusive, they are at least consistent with the conjecture that aggradation rates are higher upstream in the more anastomosed reach. Also consistent is the relatively steep slope observable in the longitudinal water profile, which can be interpreted as a wedge of sediments prograding downstream as alluviation occurs. Finally, as Robinson & Slingerland (1998) and Paola (2000) have argued, the downstream-fining itself is suggestive of preferential aggradation in the upstream reach. Although upstream bed-armouring could produce a similar downstream-fining trend, it does not adequately explain the present data, because at the time of sampling the pavement appeared to be broken and the bed was in general motion.

**SEDIMENT TRANSPORT MODELING**

The observations presented so far do not discriminate between the two hypotheses for the origin of anastomosis in the Columbia because both hypotheses predict that the degree of anastomosis will be correlated with excess sediment supply. Here, the question arises whether the Columbia channels are adjusted to maximize sediment transport rate, as suggested by Nanson & Huang (1999) and Huang & Nanson (2000). In traditional equilibrium channel theory, a river adjusts its slope, geometry and roughness to convey the water supplied and sediment discharge. Nanson & Knighton (1996) and Nanson & Huang (1999) suggested that a river might also change its number of channels to yield the same effect. Based on field observations, they asserted that a reduction in total top-width causes a multichannel network to convey more sediment per unit of total stream power, or, holding slope constant, per unit of discharge, than a single channel. Thus, if an original channel is 100 m wide and, say, 3 m deep, three channels, each 25 m wide and carrying the same discharge at the same slope, will carry more bedload because a reduced width/depth ratio (\(W/D\)) is more conducive to water flow and sediment discharge.

The hypothesis to be tested here is that the highly anastomosed reach of the Columbia River is adjusted in channel number and channel width/depth ratios to carry more sediment than a single channel, all other factors such as Manning’s \(n\) and cross-sectional shape being equal. To test the hypothesis an abstracted Columbia channel network was considered (Fig. 5) in which cumulative top-width, depth and bed-slope are kept constant at 120 m, 3 m and 10\(^{-4}\), respectively, consistent with values observed in the upstream portion of the study reach (Fig. 6 & Table 2). As Table 2 shows, width/depth ratios (defined as top-width divided by the hydraulic depth; see footnote in Table 2) range from 45 to 8. In addition, the distribution of channel widths is bimodal with the minimum occurring between 40 and 50 m. This minimum was used to separate the channels into

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**Table 1** Comparison between the upper and lower anastomosed reaches of the Columbia River in the study area.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Degree of anastomosis</th>
<th>Number of channels</th>
<th>Slope (cm km(^{-1}))</th>
<th>Number of crevasse splays*</th>
<th>Area of crevasse splays (m(^2) km(^{-1}))</th>
<th>Splay area/valley area (%)</th>
<th>Valley width (km)</th>
<th>Grain size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>High</td>
<td>3–5</td>
<td>21.5</td>
<td>10</td>
<td>c. 60 000</td>
<td>3.3</td>
<td>1.4–2.2</td>
<td>0.5–1.1</td>
</tr>
<tr>
<td>Lower</td>
<td>Low</td>
<td>1–3</td>
<td>6.8</td>
<td>1</td>
<td>c. 500†</td>
<td>0.035</td>
<td>0.7–1.8</td>
<td>0.3–0.6</td>
</tr>
</tbody>
</table>

*Average number of crevasse splays per 10 km wide transverse swath.
†Excluding avulsion site.
two groups: main channels and secondary channels. Based on these data from the Columbia River, the abstracted model contains a single channel of $W/D \approx 20$, which progressively bifurcates into second-order channels of $W/D \approx 20$ and third-order channels of $W/D \approx 10$. Interestingly, the observed width/depth ratios of main channels decrease

**Fig. 5** (left) Generic model of an anastomosing river with width/depth ($W/D$) ratios typical of the Columbia. The $W/D$ ratio progressively decreases with increasing number of channels.

### Table 2 Width/depth ratios of cross-sections in the study reach.

<table>
<thead>
<tr>
<th>Cross-section location</th>
<th>Line number*</th>
<th>Date</th>
<th>Top-width, W (m)</th>
<th>Hydraulic depth, D (m)†</th>
<th>W/D</th>
<th>Number of channels‡</th>
<th>Cumulative top-width (m)§</th>
<th>Source</th>
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</thead>
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<td>1</td>
<td>May 2000</td>
<td>125.7</td>
<td>2.86</td>
<td>44</td>
<td>1</td>
<td>125.7</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>July 2000</td>
<td>125</td>
<td>2.9</td>
<td>43</td>
<td>2</td>
<td>143</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>May 2000</td>
<td>88.9</td>
<td>2.87</td>
<td>31</td>
<td>3</td>
<td>120</td>
<td>Figueira-Rivera™</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>May 2000</td>
<td>88</td>
<td>2.88</td>
<td>31</td>
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<td>120</td>
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<tr>
<td></td>
<td>7</td>
<td>July 2000</td>
<td>90</td>
<td>2.95</td>
<td>31</td>
<td>3</td>
<td>180</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>May 2000</td>
<td>55</td>
<td>2.82</td>
<td>20</td>
<td>4</td>
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<tr>
<td></td>
<td>12</td>
<td>June 1988</td>
<td>67.6</td>
<td>2.6</td>
<td>26</td>
<td>3</td>
<td>150</td>
<td>Adams, 1999</td>
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<tr>
<td></td>
<td>13</td>
<td>June 1988</td>
<td>84.5</td>
<td>2.94</td>
<td>29</td>
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<td>20</td>
<td>July 1994</td>
<td>57.5</td>
<td>4.44</td>
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<td>4</td>
<td>100</td>
<td>Makaske, 1998</td>
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<tr>
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<td>141</td>
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<td>30</td>
<td>2</td>
<td>130</td>
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<tr>
<td><strong>Secondary channels</strong></td>
<td>2</td>
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<td>19</td>
<td>1.96</td>
<td>10</td>
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<td>May 2000</td>
<td>18.7</td>
<td>2.23</td>
<td>8</td>
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<tr>
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<td>May 2000</td>
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<td>3.64</td>
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<td>4</td>
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<td></td>
<td>18</td>
<td>June 1988</td>
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<td>1.25</td>
<td>16</td>
<td>4</td>
<td>Unknown</td>
<td>Adams, 1999</td>
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<tr>
<td></td>
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<td>July 1994</td>
<td>22.5</td>
<td>1.84</td>
<td>12</td>
<td>4</td>
<td>100</td>
<td>Makaske, 1998</td>
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<td>21</td>
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<td>22.5</td>
<td>2.1</td>
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<td>100</td>
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<tr>
<td></td>
<td>24</td>
<td>May 2000</td>
<td>21</td>
<td>2.27</td>
<td>9</td>
<td>3</td>
<td>Unknown</td>
<td>Figueira-Rivera™</td>
</tr>
</tbody>
</table>

*See Fig. 6 for locations.
†$D=$ hydraulic depth, i.e. channel cross-sectional area divided by its top-width.
‡Number of channels equals the sum of main plus secondary channels along a cross-valley transect passing through the particular channel cross-section.
§This is the summed top-width of all channels in a valley-wide transect passing through this location.
¶Main channels are defined here as having a top width greater than 50 m; all other channels are called secondary channels.
™Personal communication.
D. Abbado, R. Slingerland and N.D. Smith

with an increasing number of channels along any valley cross-section (Fig. 7), which could be interpreted as consistent with the Nanson–Huang conjecture. In contrast, the ratio for secondary channels increases. An additional important characteristic of secondary channels is that their thalwegs sit at higher elevations compared with the main channels and thus they are active only during high stage.

Sediment transport through this abstracted system is calculated under uniform and steady flow conditions assuming channels of rectangular cross-sectional shape in which:

\[ Q = VA \]  

where \( Q \) (m\(^3\) s\(^{-1}\)) is water discharge, \( V \) (m s\(^{-1}\)) is average velocity, and \( A \) (m\(^2\)) is channel cross-sectional area. Velocity, \( V \), is expressed by the Chézy formula:

\[ V = C \sqrt{R/H} \]  

where \( R \) (m) is hydraulic radius, \( S \) is channel slope and \( C \) (m\(^{1/2}\)/s) is the Chézy constant. Values for \( R \) and \( C \) are given by:

\[ R = A/(2D + W) \]  

\[ C = (1/n)R^{1/6} \]  

in which \( D \) (m) is the water depth, \( W \) (m) is the channel width and \( n \) is the Manning constant. The system of equations (1)–(4) yields the following fifth-order polynomial in \( D \):

\[ k^3WD^5 - 4D^4 - 4WD - W^2 = 0 \]  

where \( k = \sqrt{S/(nQ)} \). For fixed \( Q \), \( n \), \( S \) and width, equation (5) can be solved for \( D \), thereby yielding a specific width/depth ratio for that combination of values. In the following computations \( Q = 270 \text{ m}^3 \text{ s}^{-1}, n = 0.026, \) and \( S = 0.0001 \), consistent with typical values for the Columbia River in the study area.

Once the flow hydraulics are known, bedload and suspended load sediment transport rates are calculated by two methods: (i) the Bagnold (1977) bedload formula coupled with the Rouse (1937)
suspended sediment formulation, and (ii) the Van Rijn functions for bedload and suspended load (Van Rijn, 1984a,b). These methods were selected because they are appropriate for the grain sizes and slopes observed in the Columbia River, and because they compute both bedload and suspended load.

Solutions of the above system of equations for total sediment transport rate indicate that total sediment load is reduced as the flow is divided into additional channels (Table 3). Total transport rate decreases by approximately 11% and 21% for the Bagnold–Rouse and Van Rijn formulas, respectively. In particular, bedload transport rate, which is more important because it controls in-channel alluviation, decreases by 16% and 22%, respectively. Water velocities decrease by 2% moving from one to two channels, and 5% moving from two to four channels.

In order to generalize these conclusions, it is possible to argue that bed roughness should be greater in the smaller channels because of increased vegetation and because bedform heights there are a greater proportion of the flow depth. This, however, would only further reduce the total sediment load in the multichannel reaches. It could be argued that the idealized model does not capture the greater sinuosity and slightly higher bed elevations of the secondary channels. To address these concerns the steady-state flow field through the actual Columbia River network in the highly anastomosed reach was computed using FESWMS, a two-dimensional, finite element code for non-uniform free-surface flows. Channel geometries were traced from aerial photographs and channel bed elevations were obtained by GPS and cross-section surveys. Water depths and flow velocities at two valley cross-sections, one where the Columbia River consists of a single channel and one where it consists of three channels, were used to recompute total sediment fluxes through the two cross-sections. Predicted sediment fluxes through the reach with three channels were 25 times less than through the single channel, thus supporting the conclusions reached from the idealized model.

### DISCUSSION

The multiple channels of the Columbia do not appear to be adjusted in width, depth and number to increase water velocity and sediment transport rates over that of a single channel. These results are interpreted to mean that the Nanson & Huang (1999) hypothesis does not apply to the particular case of the Columbia River. This is not to say that the Nanson–Huang conjecture is everywhere invalidated. In cases where the cumulative top-width of multiple channels is reduced relative to a single channel, sediment transport rates will be increased. In the Columbia, however, the observed width/depth ratios and cumulative top-widths do not effect increases in sediment transport rates as the number of channels is increased.

Rather, it would appear that anastomosis of the Columbia River is a consequence of frequent avulsions (i.e. crevassing) and slow abandonment of earlier channels. High sediment flux from the

<table>
<thead>
<tr>
<th>Formula</th>
<th>Number of channels</th>
<th>Width (m)</th>
<th>Depth (m)</th>
<th>W/D</th>
<th>Water velocity (m s$^{-1}$)</th>
<th>Total bedload flux (m$^3$ s$^{-1}$)</th>
<th>Total suspended load flux (m$^3$ s$^{-1}$)</th>
<th>Total sediment load (m$^3$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagnold and Rouse</td>
<td>1</td>
<td>120</td>
<td>2.94</td>
<td>40.8</td>
<td>0.78</td>
<td>0.0061</td>
<td>0.0161</td>
<td>0.0222</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60</td>
<td>3.00</td>
<td>20</td>
<td>0.77</td>
<td>0.0058</td>
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<td>0.0214</td>
</tr>
<tr>
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<td>4</td>
<td>30</td>
<td>3.11</td>
<td>9.6</td>
<td>0.74</td>
<td>0.0051</td>
<td>0.0147</td>
<td>0.0198</td>
</tr>
<tr>
<td>Van Rijn</td>
<td>1</td>
<td>120</td>
<td>2.94</td>
<td>40.8</td>
<td>0.78</td>
<td>0.0036</td>
<td>0.0036</td>
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<tr>
<td></td>
<td>2</td>
<td>60</td>
<td>3.00</td>
<td>20</td>
<td>0.77</td>
<td>0.0033</td>
<td>0.0031</td>
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<td>30</td>
<td>3.11</td>
<td>9.6</td>
<td>0.74</td>
<td>0.0028</td>
<td>0.0026</td>
<td>0.0029</td>
</tr>
</tbody>
</table>
Spillimacheen River has overloaded the Columbia, causing high in-channel alluviation rates. These high alluviation rates increase the probability of levee overtopping as well as levee crevassing and crevasse splay formation. Increasing crevassing, in turn, creates numerous new channels through floodbasins. The new channels, flowing generally cross-valley, are usually super-elevated compared with the main channel. For this reason they are mainly active during high stage, and are slowly abandoned because of low flow velocities. Thus, long-lasting channels and complete avulsions of the main channel are tied to gradient advantages. The narrow valley means that cross-valley gradient advantage rarely occurs and the main down-valley channels remain active for thousands of years. In contrast, secondary channels on average are shorter lived. The number of channels active at any time is proportional to the rate of creation of new channels and to their average lifespan, and inversely proportional to their rate of abandonment. If the rate magnitudes are comparable and relatively constant through time, then the number of active channels at any instant is also relatively constant, the exact number being fixed by the channel lifespan. It is in this sense that anastomosis of the Columbia River is a dynamic equilibrium pattern.

It still remains for the reduction of width/depth ratio of main channels as the number of channels in a valley cross-section increases to be explained (Fig. 7). This probably reflects the fact that it is the main channels of the Columbia that transport most of the bedload. The bed elevations of the secondary channels are generally higher than the bed of the main channel, so more water than bedload is siphoned off by secondary channels. The main channel must adjust to carry its bedload with less discharge, and does so by decreasing its width/depth ratio by an amount greater than would arise from the reduction in water discharge alone. In this restricted sense the Columbia main channels are behaving as postulated by Nanson & Huang (1999).

This model of anastomosis is consistent with the correspondence between degree of anastomosis and high slope. As shown by the sediment routing model, anastomosis induces a decrease in sediment transport rates, which is manifested by differential deposition.

CONCLUSIONS

The anastomosed reach of the Columbia River can be divided into highly anastomosed and weakly anastomosed subreaches. The highly anastomosed reach occurs immediately downstream of the confluence with the high-sediment-load Spillimacheen River. The highly anastomosed reach is characterized by a higher channel gradient, a greater number of crevasse splays, a greater crevasse splay area, greater splay-area to valley-area ratio, and coarser channel-bed grain size. Circumstantial evidence indicates that aggradation rates are higher in the highly anastomosed reach as well. A rising base-level downstream does not seem to be a necessary immediate condition for anastomosis.

Calculations using Bagnold, Rouse, and Van Rijn sediment transport formulae show a decrease in sediment flux with increasing number of channels, given typical Columbia channel geometries, bed-slope, and grain size. This is contrary to the predictions of Nanson & Huang (1999), leading us to conclude that anastomosis of the Columbia River is maintained by a dynamic equilibrium between the rates of channel creation and channel abandonment.

ACKNOWLEDGEMENTS

This research was funded by the National Science Foundation under contract EAR 9811860 awarded to Rudy Slingerland and Norman D. Smith. For assistance in the field we thank Ron and Jan van Vugt, Irvine Heintz, Matt Machusick, and especially Manuel Filgueira-Rivera who also shared his cross-section data with us. The manuscript was greatly improved by the insightful comments of reviewers G.C. Nanson and B. Makaske, to whom we are grateful.

REFERENCES


Review of Amazonian depositional systems

ALLEN W. ARCHER
Department of Geology, Kansas State University, Manhattan, KS 66506, USA
(Email: aarcher@ksu.edu)

ABSTRACT

Many types of depositional system exist within the Amazon River basin and surrounding areas. These areas provide a number of valuable analogues for large-scale and tropical palaeoriver systems. Only rarely, however, are such important analogues invoked because of a lack of published information. Herein, major components are summarized among the fluvial, estuarine and coastal depositional environments of the Amazon River basin. Of particular importance in the Amazon system are the recurring depositional cyclicities that affect sedimentation. In the upper reaches of the system, yearly water-level fluctuations are related to seasonal variations in rainfall. In some areas these fluctuations exceed 10 m. The resultant flooding of vast areas of rainforest greatly affects sedimentation. In the lower reaches of the system, the dominant water-level fluctuations are related to tides. Tidal ranges are as high as 6 m at the mouth of the Amazon and tidal influences extend more than 800 km up-river. The result is a vast area of tidally influenced, freshwater environments, which are a poorly documented, but important, depositional setting.

There is a variety of river types within the Amazonian system, and the depositional environments along each are greatly affected by their differences in sediment load. Some rivers, which include the tributaries that drain the Andes, are rich in suspended sediment and have alluvial valleys containing features typical of meandering rivers, such as levees, floodplain lakes and nutrient-rich floodplains. Other rivers, with drainages entirely within extensive areas of rainforest, drain deeply weathered terrains with highly leached soils. These rivers lack suspended sediment, but have small amounts of bedload, and do not produce alluvial valleys or levees. From a sequence stratigraphy perspective, the differences among rivers have resulted in considerable variation of response to glacioeustatic-induced sea-level fluctuations and the ensuing inland changes in base level. During low stands, the Amazon deeply incised its valley for thousands of kilometres inland from the present position of the mouth. During transgression, rivers with a high sediment load vertically aggraded and kept pace with base-level rise. At the same time, the valleys of sediment-poor rivers flooded and were transformed into river-mouth lakes. These flooded valleys are not restricted to coast-proximal settings, but can be found at distances more than 1000 km inland from the modern coast.

Sediment supply has also differentially affected coastal settings along the Atlantic north and south of the Amazon mouth. The plume of turbid Amazonian water moves north-westward along the coast because of predominant winds and currents. The longshore drift of this sediment-rich plume has resulted in a low-slope, mud-dominated, prograding coast. South of the Amazon mouth, however, the lack of sediment influx has resulted in a complexly embayed erosional coastline. This southern coast consists of sea cliffs and headlands comprised of Mesozoic and younger rocks, which separate numerous small-scale macrotidal estuaries.
INTRODUCTION

Amazon drainage basin

The Amazon River system comprises the largest river system on Earth. As described by Sioli (1984), the large size of the Amazonian drainage basin, which exceeds $7 \times 10^6$ km$^2$, and the equatorial and tropical climate result in tremendous discharge and a high density of tributaries. The Amazon complex comprises the world’s largest freshwater system and contains approximately 20% of the global supply of freshwater (Oltman, 1967). The relative discharge of the Amazon (Fig. 1) has been estimated to be five times that of the Congo River and twelve times that of the Mississippi River (Gibbs, 1967a).

The slope of the Amazon drainage basin, east of the Andes Mountains, is exceedingly low. At Iquitos in Peru (Fig. 2), which is a straight-line distance of 2975 km from the Amazon mouth, the elevation of the river during low-water stage is about 114 m above sea level. Following the actual course of the river the distance from the mouth to Iquitos is 3717 km, making this the longest navigable inland waterway in the world. At Manaus in Brazil, which is a straight-line distance of about 1200 km from the mouth, the elevation above sea level is only about 15 m and the average slope to the mouth is only about 2 cm km$^{-1}$.

The Amazon drainage basin is situated between two ancient crystalline massifs, the Guiana Shield to the north and the Brazilian Shield to the south, with the western margin delineated by the Andes. The basin is elongate and is approximately 3000 km in length in an east–west direction, about 300-km wide in the eastern part and 600- to 800-km wide in the western part. This basin contains a thick sequence of Palaeozoic, Mesozoic, and Cenozoic rocks (Junk & Furch, 1985). It is the largest sedimentary basin in the world and is formed upon a Tertiary plateau consisting of a subdued area of hills and ridges, which are mostly less than 60 m above sea level (Irion, 1984). The elevation of much of the basin lies below 100 m (Fig. 2).

Sequence stratigraphy considerations

From a sequence stratigraphy standpoint, the Amazon depositional system, as defined by the drainage basin and adjacent areas of the coast and continental shelf, is exceedingly complex. During the last glaciation and lowering of sea level, the Amazon deeply incised its valley to a position approximately 2000 km upstream from the current mouth (Tricart, 1977). At that time, sea level was approximately 100 m lower and sediment was...
carried through what is now a shelfal submarine canyon and deposited in a deep-sea fan termed the Amazon cone (Milliman et al., 1975; Damuth, 1977). The glacial-age sediments of this fan are dominated by arkosic sands (25 to 60% feldspar), which suggest the presence of significantly drier climates on the Brazilian and Guiana shields during sea-level low stand (Damuth & Fairbridge, 1970). Milliman et al. (1975), however, have questioned such interpretations of dramatic climatic change.

Portions of the modern coast exhibit both submergent and emergent conditions. In general, the coast south of the Amazon mouth is emergent and is characterized by rocky headlines and embayments. In contrast, the coast to the north of the mouth, because of the tremendous amounts of suspended mud, is a depositional coast. Thus there are significant differences between these two coastal areas.

Geological evolution of the Amazon drainage basin

Prior to the Cenozoic Era, neither the Andes Mountains nor the Atlantic Ocean existed and the geological development of these features greatly influenced the subsequent development of the Amazon River system.

The Solimões and Amazon basins are Palaeozoic intracratonic basins bounded by Precambrian shields. The Purús Arch, a basement feature located west of Manaus (Fig. 2), separates these two basins. The Foz do Amazonas Basin, also known as the Marajó Basin, is a Mesozoic feature and is separated from the Amazon Basin by the Gurupá Arch, which is east of the mouth of the Rio Xingu. This arch is a structural high in the basement. The Foz do Amazonas Basin relates to the Late Jurassic to Early Cretaceous reactivation of basement structures, caused by the rifting and subsequent break-up of Gondwanaland.

The upper Amazon, to the west of Manaus, probably drained to the west prior to the uplift of the Andes. During the Miocene, the area to the east was a vast brackish basin, which changed slowly to a freshwater environment (Beurlen, 1970). Miocene deposition of coarse colluvial material within the basin does not agree with present-day depositional conditions related to the dense forest cover. This suggests the former existence of a drier, more seasonal climate and would have occurred when the river profile was graded to a lower sea level.
Types of Amazonian rivers

The rivers and tributaries within the Amazon system exhibit significant differences owing to variations in sediment types and supply, vegetation, and relief and geology of the drainage basins. Wallace (1853) provided a useful and widely accepted river classification, subsequently popularized by Sioli (1950), based upon optical properties. The rivers include whitewater, which are light coloured and very turbid owing to high concentrations of suspended sediments, blackwater, which lack inorganic suspended sediment but have a significant concentration of humic compounds, and clearwater, which lack suspended materials or humic compounds.

Whitewater rivers

This river type includes the Rio Amazonas and its tributaries, primarily the Rios Japurá, Putumayo, Napo, Marañón, Ucayali, and Madeira, which drain the Andes. The Madeira is the most eastern of this series of whitewater rivers. The headwaters consist of readily weathered volcanic and sedimentary rocks, yielding very high sediment loads (Dunne et al., 1998). The light colours in these rivers, which are commonly yellowish or brownish and not actually white, relate to high concentrations of dissolved ions and suspended sediment. Gibbs (1967a,b) estimated that these tributaries comprise only about 12% of the Amazon drainage basin, but supply 86% of the dissolved ions and 82% of the suspended sediment. More recent estimates suggest that 90 to 95% of the suspended sediment is derived from the Andes (Meade et al., 1985; Meade, 1994).

Whitewater rivers are characterized by meandering channel patterns and the bank erosion produces an abundance of floating and partially submerged trees and other types of terrestrial plant debris. The water is relatively rich in nutrients and supports the growth of floating herbaceous vegetation (as both floating meadows and islands). Runoff draining the rainforest does not have typical blackwater colours because organics are adsorbed on to clay particles where they are subsequently decomposed (Jordan, 1985). Erosion and scour along whitewater rivers, such as the Rio Amazonas, can undercut banks and result in long stretches of shoreline catastrophically slumping into the river. These phenomena, termed terras caídas (fallen land), can be quite dramatic and the resultant waves have been known to overwhelm small boats (Sioli, 1975).

Floodplains include relict meanders, levees, back swamps and floodplain lakes. The floodplain associated with whitewater rivers is termed várzea (Pires & Prance, 1985). Owing to high suspended loads, rapid rates of vertical accretion have kept pace with base-level rise. Bedload of the Rio Amazonas consists primarily of fine-grained sand. In some places there are small amounts of gravel, particularly near bedrock outcrops. Unlike many river systems, however, the average grain size and degree of sorting within the mainstem bed sediments is essentially constant along the 3300 km reach between Iquitos and Belém (Nordin et al., 1980, 1981).

Blackwater rivers

The term blackwater is somewhat misleading because the water within such rivers is actually relatively clear. For the Rio Negro, Sioli (1967) compared the river water to slightly contaminated distilled water and stated that the river water has the appearance of very weak tea. The low levels of suspended sediment, lack of dissolved nutrients and acidic conditions prevent the growth of floating vegetation.

Sandy podzolic soils give rise to the blackwater rivers; the colours come from humic acids leached from leaf litter (Leenheer, 1980; Jordan, 1985). The high concentration of organics creates acidic concentrations and the pH of blackwater rivers is commonly about 4. Although blackwater rivers lack suspended sediments, they can have significant amounts of sand-rich bedload. One result of the low pH is that these bedload sands are almost exclusively quartzose because less stable mineral grains are readily dissolved (Leenheer & Santos, 1980).

The combined effects of lack of alluviation and extensive plant stabilization result in the floodplains of blackwater rivers not having levees, backswamps and floodplain lakes. Thus, riverbanks are more stable than in whitewater systems and the influx of plant debris into the river is minimal. Areas of flooded forest are termed igapó (Pires &