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

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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'.

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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°C in January and July, respectively (Farley, 1979).

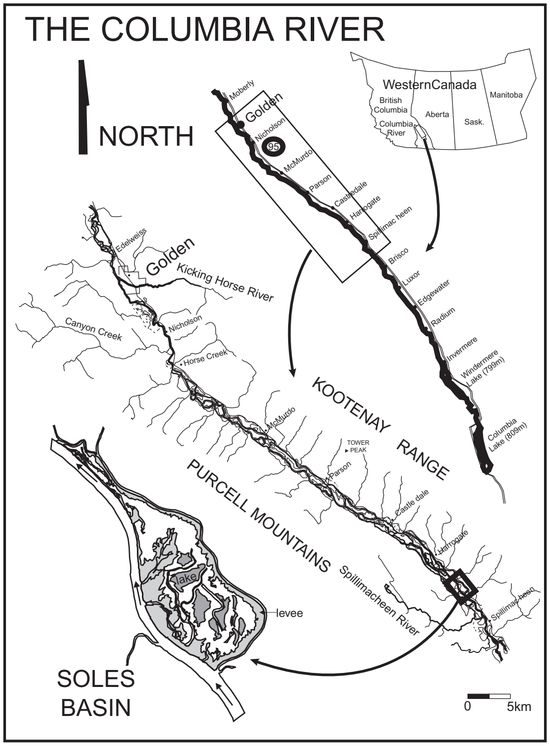

Fig. 1 Location of the study area. The Columbia River flows north-north-west between the Kootenay Range of the Rocky Mountains and the Purcell Mountains. Soles Basin, selected as a typical floodplain of the anastomosing reach, lies immediately downstream of the Spillimacheen River, an important tributary.

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 splays 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 km^2) and the Kicking Horse River (drainage basin of 1850 km^2), 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, 1986) and 10–20% (D.G. Smith, as reported in Makaske, 1998).

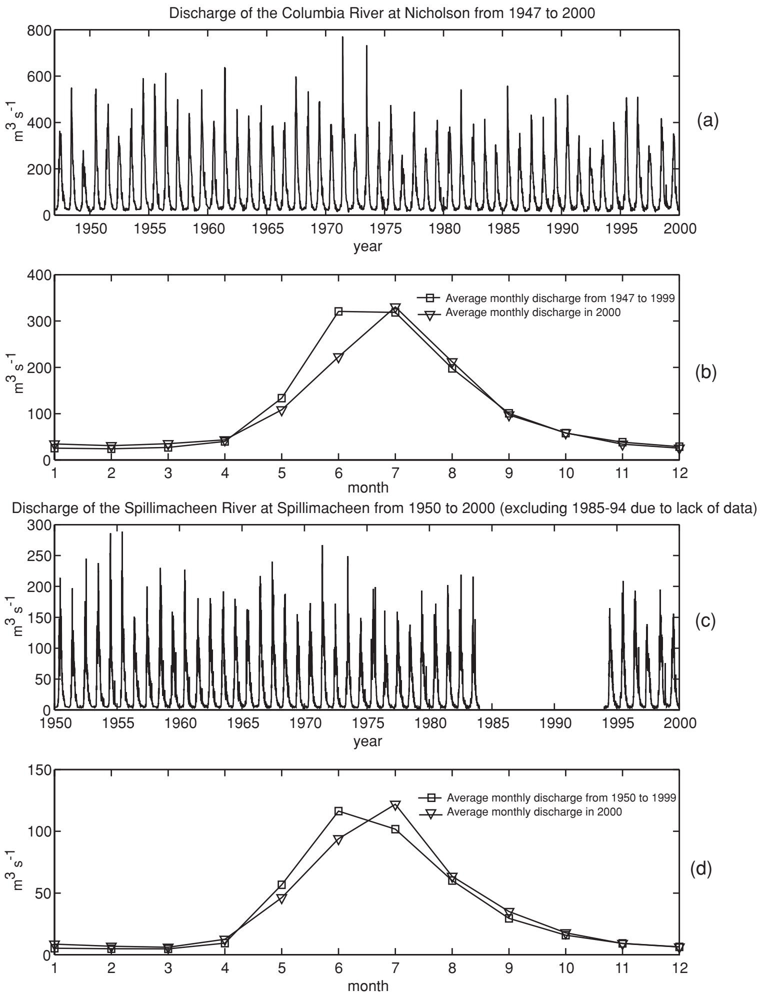

Fig. 2 Discharge data for the rivers studied. (a) Discharge of the Columbia River at Nicholson 1947–2000. (b) Average monthly discharge of the Columbia over the interval 1947–1999 compared with year 2000 average monthly discharge. (c) Discharge of the Spillimacheen River at Spillimacheen 1950–2000. (d) 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).

Hydrology

Hydrographs 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 $m^3 s^{-1}$), and maximum discharge occurs in June and July (average = 321 $m^3 s^{-1}$), 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 $m^3 s^{-1}$ 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 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 $m^3 s^{-1}$) 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.

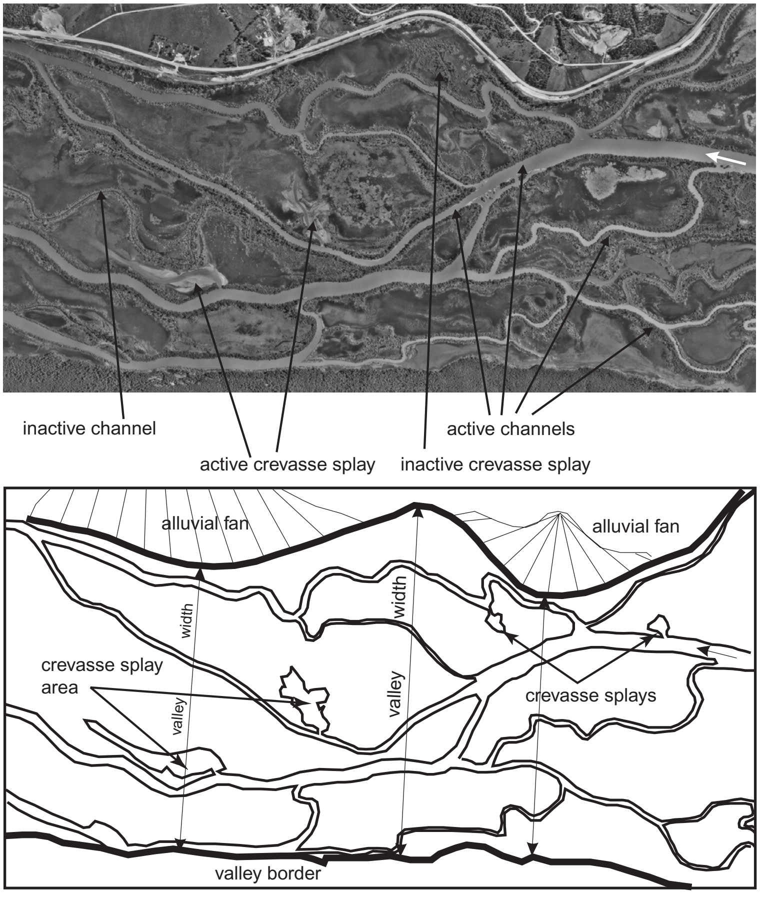

Fig. 3 Morphological elements of the river system. (Top) 1998 aerial photograph of the Columbia River showing active and inactive channels and crevasse splays. (Bottom) Definition sketch showing how crevasse splay area, alluvial fan area, and valley width were computed. See Fig. 6 for location.

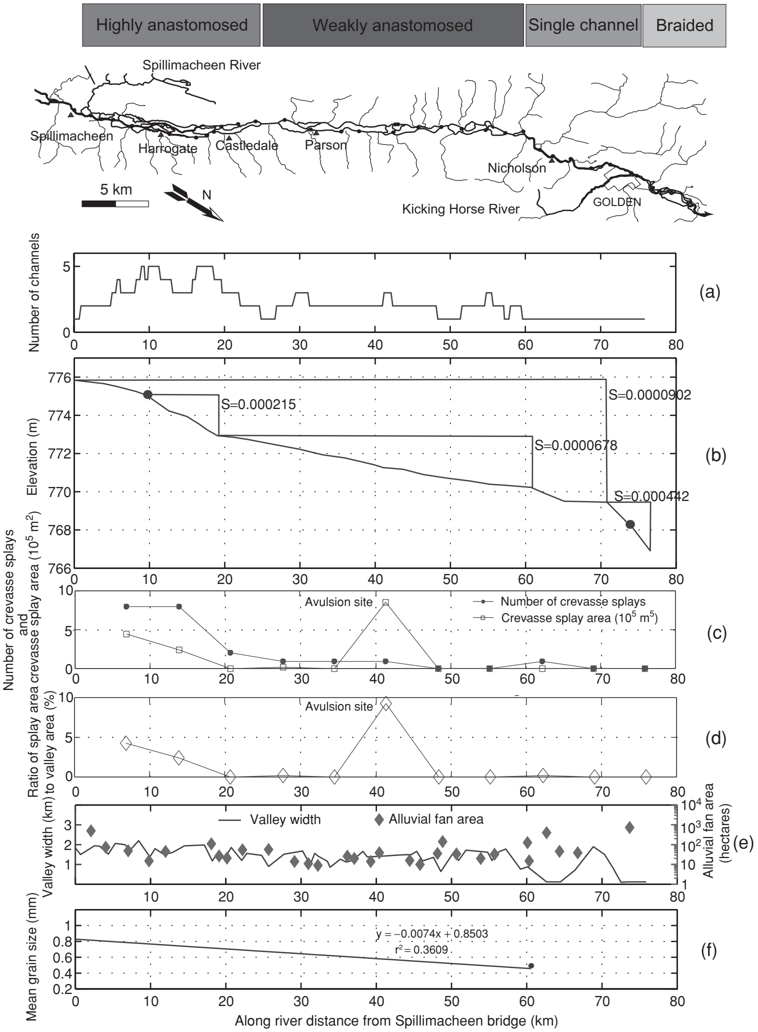

Fig. 4 Comparison of selected morphological parameters of the Columbia River. (a) Number of channels. (b) Elevation. (c) Number and area of splays. (d) Splay/valley-area ratio. (e) Valley width and alluvial fan area. (f) Mean grain size. See text for explanations.

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.

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 floodbasin 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

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

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

*Average number of crevasse splays per 10 km wide transverse swath.
†Excluding avulsion site.

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 MODELLING

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 two groups: main channels and secondary channels. Based on these data from the Columbia River, the abstracted model contains a single channel of $W/D \cong 20$, which progressively bifurcates into second-order channels of $W/D \cong 20$ and third-order channels of $W/D \cong 10$. Interestingly, the observed width/depth ratios of main channels decrease

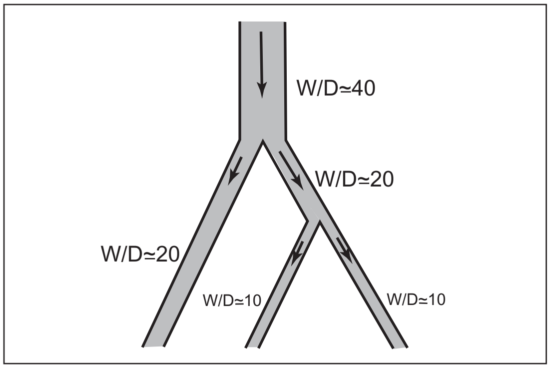

Fig. 5 (*left*) Generic model of an anastomosing river with width/depth (*W*/*D*) ratios typical of the Columbia. The *W*/*D* ratio progressively decreases with increasing number of channels.

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

Cross-section location	**Line number***	**Date**	**Top-width, *W* (m)**	**Hydraulic depth, *D* (m)†**	***W*/*D***	**Number of channels‡**	**Cumulative top-width (m)§**	**Source**
Main channels¶	1	May 2000	125.7	2.86	44	1	125.7	This study
	4	July 2000	125	2.9	43	2	143	This study
	5	May 2000	88.9	2.87	31	3	120	Filgueira-Rivera**
	6	May 2000	88	2.88	31	3	120	Filgueira-Rivera**
	8	July 2000	90	2.95	31	3	180	This study
	11	May 2000	55	2.82	20	4	188	Filgueira-Rivera**
	12	June 1988	67.6	2.6	26	3	150	Adams, 1999
	17	June 1988	84.5	2.94	29	4	160	Adams, 1999
	20	July 1994	57.5	4.44	13	4	100	Makaske, 1998
	22	May 2000	141	3.12	45	1	141	Filgueira-Rivera**
	23	May 2000	101.6	3.34	30	2	130	Filgueira-Rivera**
Secondary channels	2	May 2000	19	1.96	10	2	143	Filgueira-Rivera**
	3	May 2000	18.7	2.23	8	2	143	This study
	7	May 2000	23.2	2.07	11	3	120	Filgueira-Rivera**
	9	May 2000	13.7	2.25	6	3	180	Filgueira-Rivera**
	10	May 2000	38	2.95	13	4	172	Filgueira-Rivera**
	13	June 1988	30.4	1.58	19	5	Unknown	Adams, 1999
	14	May 2000	38.9	2.9	13	5	Unknown	Adams, 1999
	15	May 2000	31	3.64	9	5	Unknown	Filgueira-Rivera**
	16	May 2000	35	3.49	10	4	Unknown	Filgueira-Rivera**
	18	June 1988	20.3	1.25	16	4	Unknown	Adams, 1999
	19	July 1994	22.5	1.84	12	4	100	Makaske, 1998
	21	July 1994	22.5	2.1	11	4	100	Makaske, 1998
	24	May 2000	21	2.27	9	3	Unknown	Filgueira-Rivera**

*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.

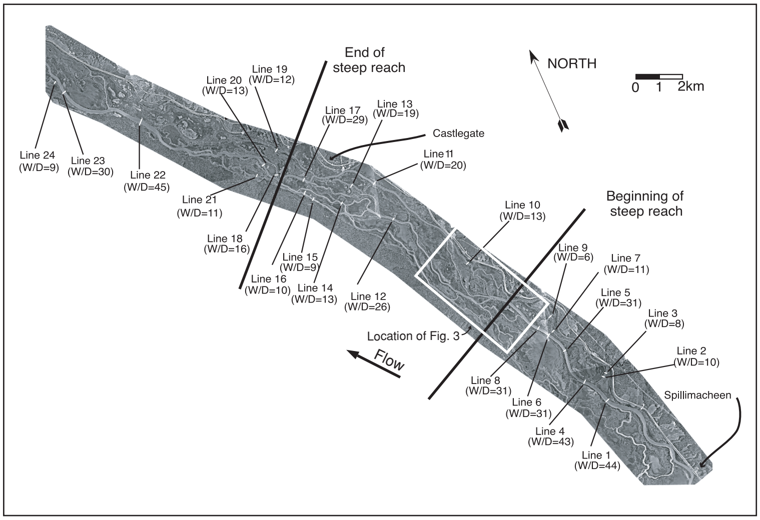

Fig. 6 Aerial photograph collage of the highly anastomosed reach of the Columbia River. Measured cross-sections are indicated by a white line; W/D ratio in parentheses.

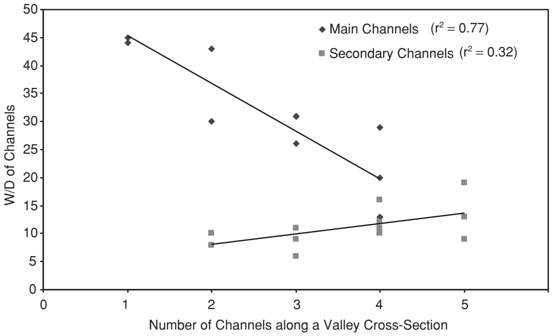

Fig. 7 Width/depth ratios of channels as a function of number of channels passing flow through any valley cross-section. Main channels are defined as those possessing widths greater than 50 m.

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:

$$Q = VA \tag{1}$$

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

$$V = C\sqrt{RS} \tag{2}$$

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

$$R = A/(2D + W) \tag{3}$$

$$C = (1/n)R^{1/6} \tag{4}$$

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:

$$k^3W^5D^5 - 4D^2 - 4WD - W^2 = 0 \tag{5}$$

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 $Q = 270\ \mathrm{m^3\,s^{-1}}$, $n = 0.026$, 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)

Table 3 Theoretical sediment transport magnitudes as a function of sediment transport formula and number of channels: $Q \approx 270\ \mathrm{m^3\ s^{-1}}$.

Formula	**Number of channels**	**Width (m)**	**Depth (m)**	***W/D***	**Water velocity ($\mathrm{m\ s^{-1}}$)**	**Total bedload flux ($\mathrm{m^3\ s^{-1}}$)**	**Total suspended load flux ($\mathrm{m^3\ s^{-1}}$)**	**Total sediment load ($\mathrm{m^3\ s^{-1}}$)**
Bagnold and Rouse	1	120	2.94	40.8	0.78	0.0061	0.0161	0.0222
	2	60	3.00	20	0.77	0.0058	0.0156	0.0214
	4	30	3.11	9.6	0.74	0.0051	0.0147	0.0198
Van Rijn	1	120	2.94	40.8	0.78	0.0036	0.0336	0.0372
	2	60	3.00	20	0.77	0.0033	0.0310	0.0343
	4	30	3.11	9.6	0.74	0.0028	0.0264	0.0292

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

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.

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