Chapter 4
Influences on river morphology in a sediment-dominated system

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Abstract

Rivers dictate landscape evolution, exerting controls on erosional processes, setting boundary conditions for hillslope processes and governing the height limits of mountain ranges. Material eroded through hillslope processes and bedrock channel incision is eventually transported by alluvial (transport-limited) channels. The morphology of these channels is governed by a number of drivers including tectonic processes, climate, and local lithology that influence the river system over a range of timescales. This paper explores these drivers and presents a conceptual model that links these drivers to channel morphology and formation of riparian ecosystem in the Chilko- Chilcotin River system of British Columbia.

Introduction

River channels play a major role in landscape evolution, transmitting signals of climactic or tectonic change across the landscape, controlling the timescale of response of the landscape to these changes, setting the boundary conditions for hillslope processes and eventually governing the height limits of mountain ranges (Seidl and Dietrich, 1992; Seidl, 1993; Howard et al., 1994; Sklar and Dietrich, 1998; Whipple and Tucker, 1999; Whipple et al., 2000, Selander, 2004). Bedrock-dominated (detachment-limited) reaches are responsible for incision and channel lowering, which is widely studied and readily quantifiable via the stream power incision law (e.g. Sklar and Dietrich, 1998; Stock and Montgomery, 1999; Whipple and Ticker, 1999; Kirby and Whipple, 2001; Dietrich et al., 2003). Alluvially-dominated (transport-limited) channel reaches are governed by the ability of the river to mobilize and transport sediment, which can be explained through systems of empirical laws (e.g. Gilbert, 1914; Montgomery and Buffington, 1997; Dade and Friend, 1998; Eaton et al., 2004). Though detachment-limited channels may ultimately control high-relief landscapes (Selander, 2004; Whipple, 2004), transport-limited channels move the majority of sediment, have a high temporal variability in form, and their dynamics can drive habitat formation or alteration for aquatic organisms (Dietrich et al., 1979; Dietrich, 1987; Church, 2002; Ward et al., 2002; Harrison et al., 2011).

An alluvial channel's ability to mobilize and transport sediment directly influences the plan-form and long profile morphology of a fluvial system, which is in turn dependent on the broad relationship between the river channel, landscape denudation, and topographic uplift. Here, a fluvial system is defined as being in dynamic equilibrium when the long-profile shape of the channel has a smooth, concave-up form (Gilbert, 1877) in a setting where topographic uplift is balanced by overall landscape denudation (e.g. Montgomery, 2001) (Figure 1). This is an idealized circumstance, but serves as a reference frame from which to examine influences on channel morphology in a disequilibrium system. Perturbations in first-order fluvial characteristics (e.g. changes in channel slope, discharge, base level) have a direct impact on the channel geometry, the amount and size of sediment a river can carry, whether the system will aggrade or incise, and eventually will control the overall physical morphology of the system. Although these perturbations can take place on relatively fast timescales, an alluvial system can remain in disequilibrium long after the initial disturbance (Collins and Montgomery, 2011), as local perturbations can propagate both upstream and downstream throughout a system (Montgomery and Buffington, 1998).

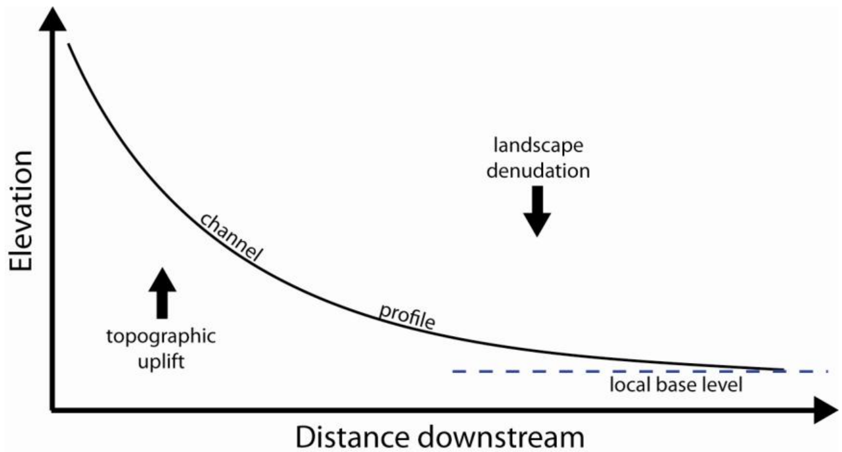

Figure 4.1. Idealized longitudinal profile for a stream channel in equilibrium with topographic uplift and landscape denudation.

Processes that govern the morphology of a fluvial system can be grouped into three categories: **(1)** *Tectonic processes*; **(2)** *Climatic/ hydrologic regime and changes therein*; and **(3)** *Downstream changes in bedrock lithology* (Figure 2). Tectonic uplift or subsidence of a catchment will produce a change in base level resulting in either a wave of incision propagating upstream (uplift, base level fall) (Whipple, 2004), or aggradation (subsidence, base level rise) as the channel adjusts. Climatic changes directly influence the amount of water that is available to move into the channel network, the amount of weathering that takes place within the catchment, and the amount of sediment that is supplied to the channel and the stream's ability to move this sediment. Variations in competence of bedrock lithology underlying a channel will limit or enhance the channel's ability to incise vertically and produce local and reach-scale changes in channel slope.

These drivers and others behind the morphology of a fluvial system are explored in this paper with respect to their impacts on the morphology of the Chilko and Chilcotin River systems (CCR) in the southern Coast Mountains of British Columbia. This is one paper in a volume of work that explores the ecosystem of the CCR and its physical and biological drivers.

Setting

The Chilko River is part of the larger Fraser River watershed (Tribe, 2002), and is situated along the eastern flank of the Coast Mountains of British Columbia, and flows northeast out of Chilko Lake (Holland, 1964; Desloges and Gilbert, 1998) (Figure 3). The Coast Mountains are a complex assemblage of Mesozoic terranes accreted to the North American continent during various stages of orogenesis (Umhoefer et al., 1994; Garber, this volume). Presently, the Coast Mountains are experiencing uplift due to post-glacial rebound (Clague and James, 2002; Farley et al., 2001) and possible tectonic forcing (Matthews, 1991; Parrish, 1983; Rohr and Currie, 1997; McCaffrey et al., 2007), though this remains debated (Garber, this volume).

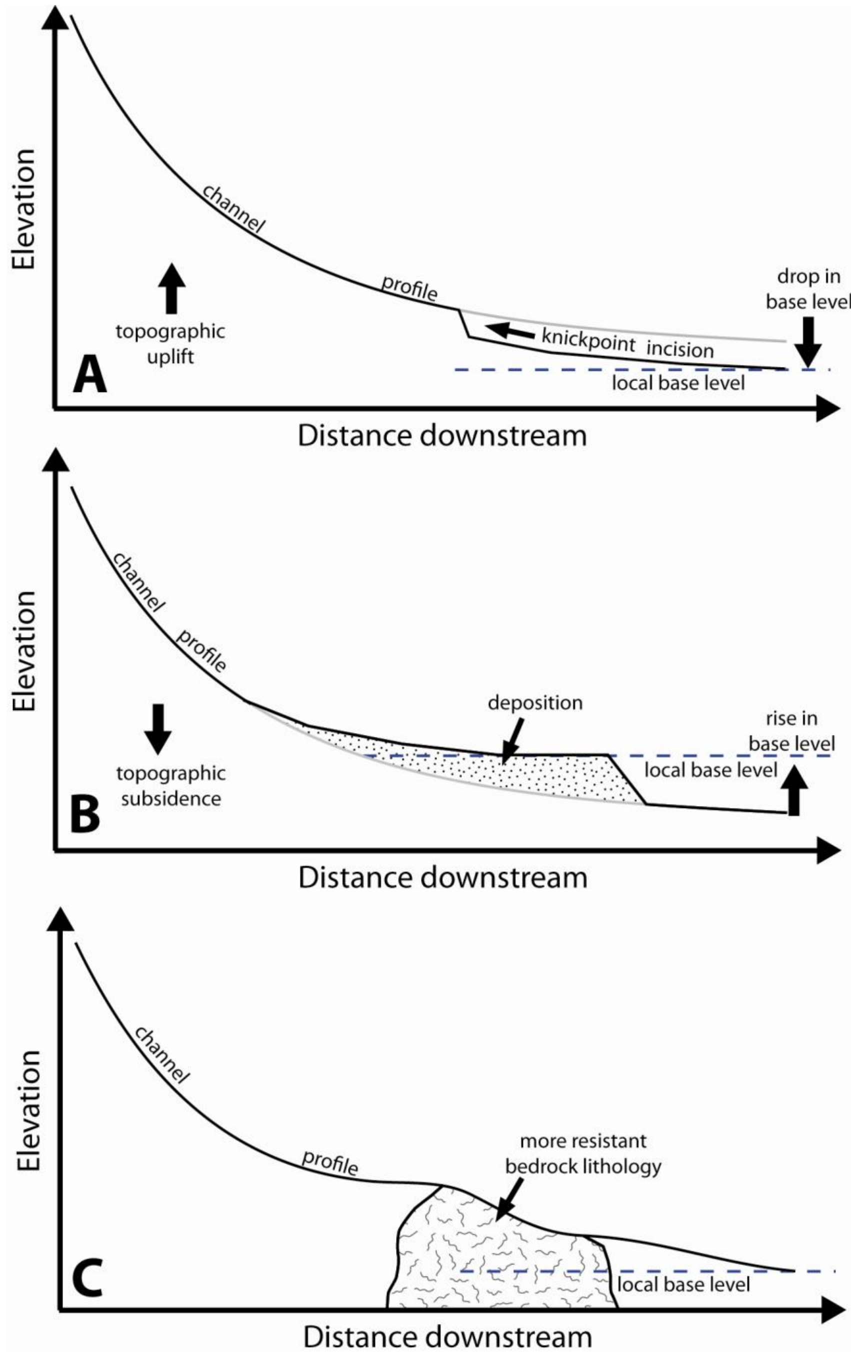

Figure 4.2. Perturbations to the longitudinal profile of a stream channel. **(A)** Relative drop in base level via tectonic uplift of the catchment or local base level fall. **(B)** Relative rise in base level via tectonic subsidence of the catchment or local base level rise. **(C)** Variations in downstream lithology. See text for details.

The Coast Ranges have experienced varying degrees of glaciation throughout the Quaternary (Stumpf et al., 2000; Clague and James, 2002; Austin, this volume), the most recent being the Wisconsinan Fraser glaciation circa 20-15 ka (Stumpf et al., 2000). At present, approximately 10% of the catchment area of Chilko Lake is covered by glaciers (Desloges and Gilbert, 1998).

Downstream of Chilko Lake, the Chilko and Chilcotin River system flows through a mixture of bedrock and glacial outwash deposits (Garber, this volume)(Figures 2 and 3). These loosely consolidated outwash tills combined with the sediment influx provided by the Taseko River provide a readily available source of sediment for the system (e.g. Hartman and Clague, 2007).

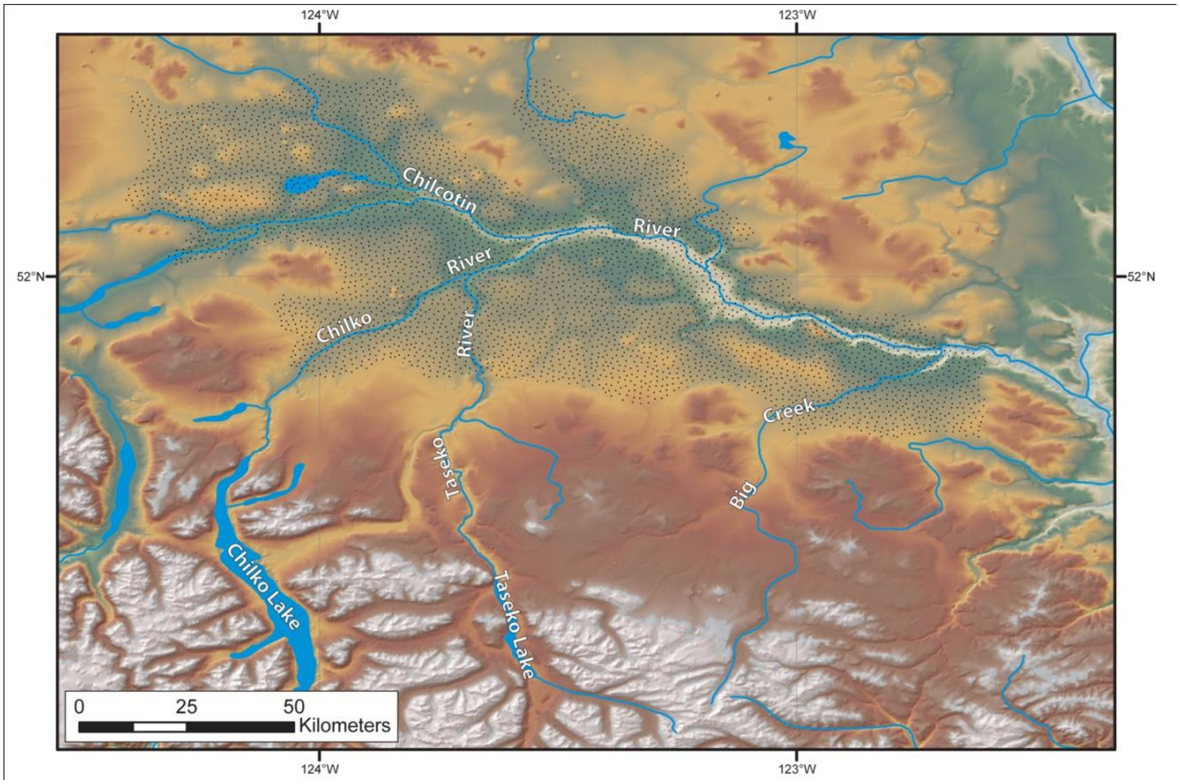

Figure 4.3. Hillshade and digital elevation model of the Chilko- Chilcotin Rivers. Stippled region shows approximated extent of glacial outwash sediments in the Chilko-Chilcotin catchments.

Channel morphology

Primary Drivers and Processes: *Tectonics*

Changes in base level as a result of tectonic or isostatic forcing has a direct impact on the longitudinal profile form of a fluvial channel (Figure 2). A rapid lowering of base level via a drop in eustatic sea level or tectonic/ isostatic uplift of the catchment will produce a knickpoint wave (defined here as a transitory, locally oversteepened reach) at the channel mouth. This wave will then propagate upstream along the main channel and branch out at tributary junctions (Whipple, 2004; Selander, 2004; Schildgen et al., 2007; Wobus et al., 2007). Though this base level drop may be relatively instantaneous over geologic timescales, the landscape response and knickpoint propagation speed is highly dependent on a large number of parameters including drainage area, pre-knickpoint slope, lithology and amplitude of base level fall (e.g. Loget and van der Dreissche, 2009), leaving the system in disequilibrium for an indeterminate amount of time.

Tectonic subsidence of a catchment or eustatic sea level rise will produce a relative rise in base level, leading to an opposite effect on long-profile channel form (Figure 2). A rise in base level decreases the slope at the channel mouth, decreasing the velocity of the water and amount of sediment the channel can carry. This decrease in capacity causes the river to aggrade in order to compensate for the rise in base level.

Climatic changes

Changes in the climatic regime of a catchment have direct impacts on the amount of water and sediment in the system. A cooler, wetter climate conducive to glaciation (e.g. Austin, this volume) would see a decrease in channel discharge with an increase in sediment flux from glacial erosion into the system. Warm, wet climates will see an increase in stream discharge and in the amount of suspended and dissolved sediment produced by increased rates of chemical weathering. Dry climates would lead to a decrease in discharge, and a decrease in the amount of sediment moved by the system. For example, glacial topography in previously glaciated drainages in southern British Columbia has a strong influence on channel organization, discharge and sediment transport (Brardinoni and Hassan, 2007; Collins and Montgomery, 2011). Additionally, large-scale global climatic changes (e.g. glacial-interglacial transitions) can produce a fall or rise in base level, respectively, leading to the same effects as tectonic forcing of a fluvial channel.

Lithologic changes

Channel steepness and bedrock lithology are directly related via the stream-power incision law (Whipple and Tucker, 1999; Whipple, 2004):

$$E = KA^mS^n \qquad \textbf{(1)}$$

where E is the erosion rate, A is the upstream drainage area, S is local channel slope, K is a constant that takes into account bedrock erodibility, and m and n are empirically-derived exponents.

A substrate that is less resistant to erosion requires less stream power to incise into, and therefore the channel can maintain a lower slope (Figure 2). A higher amount of stream power is required to maintain a constant erosion rate through highly resistant bedrock; therefore the channel must increase its slope to adjust.

Sediment Transport

Alluvial river systems generally exhibit a low transport to supply ratio (Montgomery and Buffington, 1997), though how and when sediment is transported by a river remains integral to its plan-form morphology. Changes in the delivery of sediment and discharge result in a range of channel form adjustments (Harrison et al., 2011), namely the development of mid-channel bars (Wilkinson et al., 2008).

The amount and size of sediment that a river can carry is determined by the discharge and channel slope through the relationship (Anderson and Anderson, 2010):

$$\tau_b = \rho_w g H * \sin(\alpha) \qquad \textbf{(2)}$$

where τ_b is the shear stress on the bed of the channel required for sediment motion, ρ_w is the density of water, H is the height of the water column (used as a proxy for discharge, an increase in discharge directly relates to an increase in H), and α is the local channel slope. In a broad sense, increasing discharge and flow velocity increases the amount of shear stress imposed on the channel bed and the amount of sediment that is transported via bed load or entrained.

Conceptual Model

A conceptual model for river morphology is presented within the context of the Chilko and Chilcotin River systems, ultimately describing the influence of river morphology on the ecosystem as a whole (Figure 4). The main drivers of this model (tectonics, climate, and lithology) are explained above; here the focus is on the links between intermediate outcomes/ processes and channel morphology/ habitat formation.

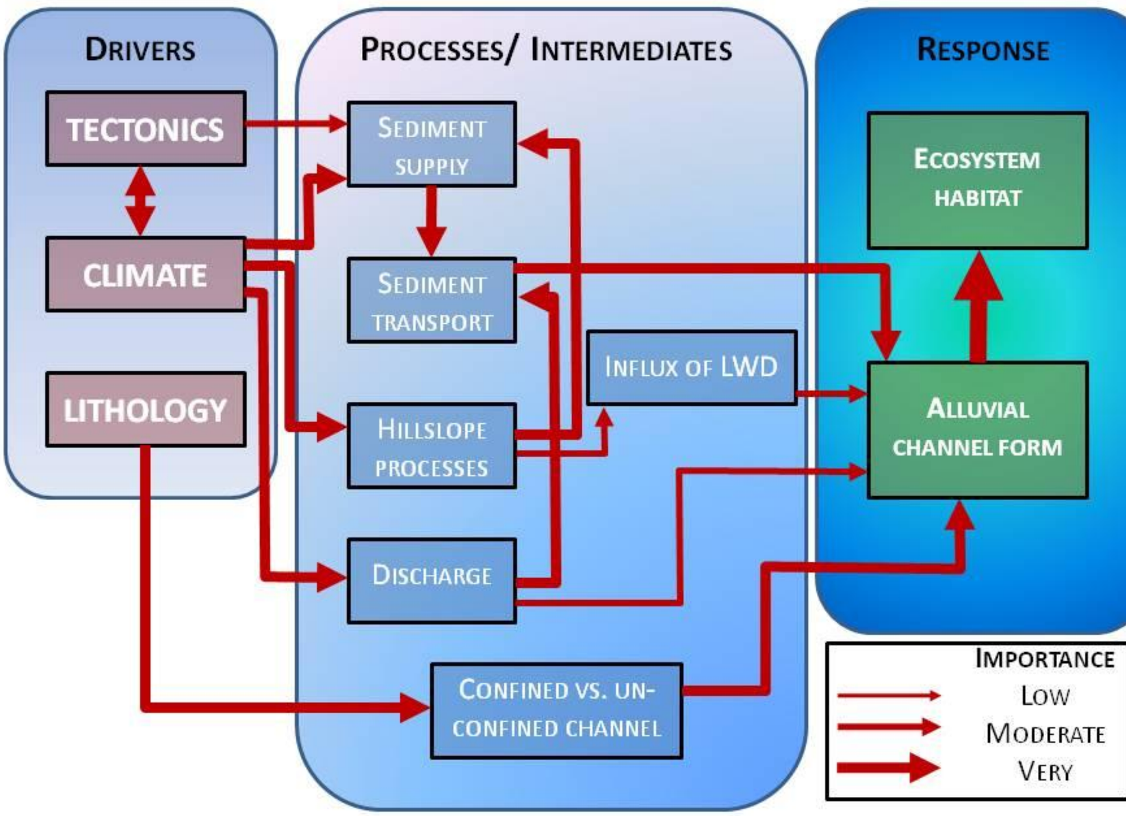

Figure 4.4. Conceptual model outlining the drivers, intermediates and processes, and outcomes behind river morphology in a sediment-dominated system such as the CCR. See text for details.

Confined vs. un-confined channels

Between Chilko Lake and the confluence with the Fraser River, the Chilko- Chilcotin River (CCR) system flows through reaches of both glacial till, Mesozoic bedrock, and ~20 Ma Chilcotin group basalt flows (Garber, this volume). Where the CCR has incised through the glacial deposits into the underlying bedrock, its slope has adjusted such that through the bedrock reaches the CCR has enough stream power to erode, while upstream the slope decreases and the system is depositing sediment (Figure 5). These bedrock and alluvial reaches are referred to as “confined” and “unconfined” channel reaches, respectively. Above and below these confined reaches, the channel width increases, slope decreases, and velocity decreases leading to deposition of sediment and formation of gravel bars and islands (Figure 6).

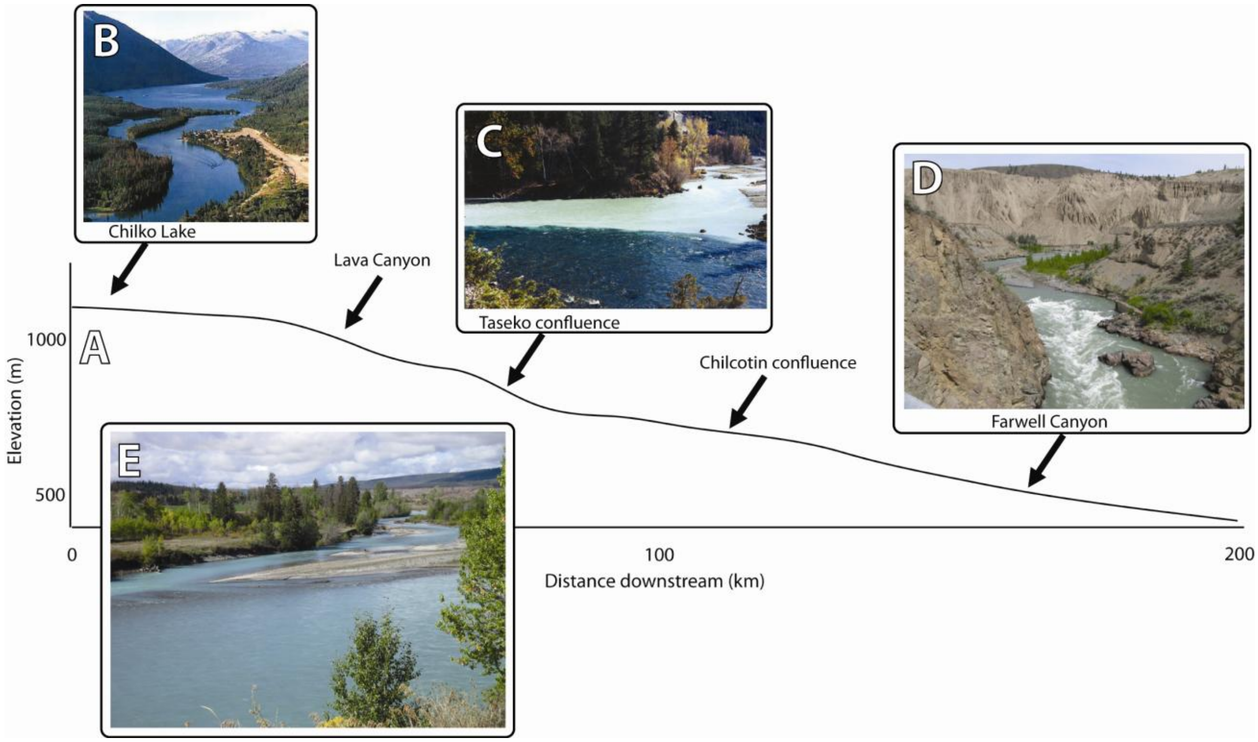

Figure 4.5. (A) Elevation profile for the Chilko and Chilcotin Rivers downstream of Chilko Lake to the Fraser River confluence. **(B)** Aerial photo of Chilko Lake. **(C)** Photo of the Chilko- Taseko confluence. **(D)** Photo of massive glacial outwash deposits and a confined reach in Farwell Canyon. **(E)** Photo of an unconfined reach of the Chilcotin River. Note that the channel is braided in both the confined and unconfined reaches, but the width of the braidplain is limited in the confined reaches. All photos courtesy Google Earth.

Figure 4.6. Photograph of a gravel bar and island along the Chilcotin River, people for scale in foreground. Image courtesy Jeff Mount.

Hillslope processes, sediment input and channel form

Erosional and transport processes acting on hillslopes are ultimately responsible for the majority of sediment input to a river system (e.g. Roering, 2008; Anderson and Anderson, 2010, Cookingham, this volume). In the case of the Chilko and Chilcotin Rivers and other glacially-dominated systems where sediment supply is greater than the channel's transport ability (e.g. Montgomery and Buffington, 1997), alluvial reaches will dominate the unconfined regions of the system. This sediment supply to the CCR comes from two major sources: (1) input from the Taseko River, and (2) rapidly eroding glacial outwash terraces (Austin, this volume). Similar to the Chilko River the Taseko has a lake at its head, although Taseko Lake is much smaller than Chilko Lake (Figure 3), leading to a shorter residence time of sediment in the lake and more sediment flux into the downstream system. In these sediment-dominated reaches of the CCR (Figure 3), the channel will migrate laterally over time through pool scour and erosion of cut banks (Dietrich, 1987). This channel migration, combined with gravel bar growth provides ideal, low-velocity habitat for salmonids and other aquatic animals (Trush et al., 2000; Harrison et al., 2011).

Influx of LWD

Large woody debris (LWD) has been shown to be a key component in morphology of river systems (e.g. Abbe and Montgomery, 2003; Wohl et al., 2010). The primary influx of LWD comes from hillslope processes (Cookingham, this volume) and episodic flood events that mobilize LWD present on the floodplain. LWD that becomes lodged along the side of the channel or along shallow mid-channel bars can produce localized regions of reduced flow velocity and subsequent deposition of material. This can produce a positive-feedback system which can entrain other pieces of LWD and increase the areal extent of lowered flow velocity (Figure 7).

Figure 4.7. Photo of LWD entrained on an island in the Chilcotin River. Note the large areal extent of the LWD and the perturbations to channel flow along its margins. Image courtesy Robyn Suddeth.

Summary

Many factors influence the morphology of a river system. Long time scale processes (e.g. tectonic changes) through short-term drivers (episodic glaciations, climatic changes) ultimately determine first-order channel characteristics such as slope, discharge, and capacity. With respect to the CCR system, large amounts of glacial outwash deposits and influx of hillslope material provide the sediment for the channel to transport. The amount of material that the CCR system can transport is directly related to the discharge and slope, which are in turn driven by climate and bedrock lithology. This sediment transport, combined with input of LWD from hillslopes, dictates the formation of riparian habitat in locations where channel slope and flow velocity (discharge) allow for deposition.

References

Abbe, T. and Montgomery, D., (2003) Patterns and processes of wood debris accumulation in the Queets river basin, Washington. Geomorphology (51) p. 81-107.

Anderson, R.S. and Anderson, S.P., (2010) Geomorphology: The Mechanics and Chemistry of Landscapes. Cambridge University Press, 637 p.

Brardinoni, F., and M. A. Hassan (2006), Glacial erosion, evolution of river long profiles, and the organization of process domains in mountain drainage basins of coastal British Columbia, J. Geophys. Res., 111, F01013, doi:10.1029/2005JF000358.

Church, M., (2002) Geomorphic thresholds in riverine landscapes, Freshwater Biology (47) p. 541-557.

Clague, J.J., and James, T.S., (2002) History and isostatic effects of the last ice sheet in southern British Columbia. Quaternary Science Reviews (21) p. 71-87.

Collins, B.D., and Montgomery, D.R., (2011) The legacy of Pleistocene glaciation and the organization of lowland alluvial process domains in the Puget Sound region, Geomorphology (126) p. 174-185, doi:10.1016/j.geomorph.2010.11.002

Crosby, B.T., Whipple, K.X., Gasparini, N.M., Wobus, C.W. (2007) Formation of hanging valleys: Theory and simulation, Journal of Geophysical Research- Earth Surface (112) F3 doi:10.1029/2006JF000566

Dade, W.B. and Friend, P.F, (1998) Grain-size, sediment-transport regime, and channel slope in alluvial rivers, Journal of Geology (106) p. 661-676.

Desloges, J.R. and Gilbert, R. (1998) Sedimentation in Chilko Lake: a record of geomorphic environment of the eastern Coast Mountains of British Columbia, Canada, Geomorphology (25) p. 75-91.

Dietrich, W. E., J. D. Smith, and T. Dunne (1979), Flow and sediment transport in a sand bedded meander, J. Geol., 87, 305–315, doi:10.1086/628419.

Dietrich, W. E. (1987), Mechanics of flow and sediment transport in river bends, in River Channels: Environment and Process, edited by K. S. E. Richards, pp. 179–227, Blackwell, Oxford, U. K.

Dietrich WE, Bellugi D, Heimsath AM, Roering JJ, Sklar L, Stock JD. 2003. Geomorphic transport laws for predicting the form evolution of landscapes. In *Prediction in Geomorphology*, ed. PRWilcock,RIverson, pp. 103–32. Washington, DC: Am. Geophys. Union

Eaton, B.C., Church, M., Millar, R.G. (2004) Rational regime model of alluvial channel morphology and response, Earth Surface Processes and Landforms (29) p, 511-529, doi:10.1002/esp.1062

Farley, K.A., Rusmore, M.E., and Bogue, S.W., (2001) Post---10 Ma uplift and exhumation of the northern Coast Mountains, British Columbia. Geology (29) p. 99-102.

Gilbert, G.K. (1877) Geology of the Henry Mountains (Utah). Washington, DC: U.S. Gov. Print Off. 160 p.

Gilbert, G.K. (1914) The transportation of debris by running water. Washington, DC: U.S. Gov. Print Off, 200 p.

Harrison, L. R., C. J. Legleiter, M. A. Wydzga, and T. Dunne (2011), Channel dynamics and habitat development in a meandering, gravel bed river, Water Resources Research (47) W04513, doi:10.1029/2009WR008926.

Hartman, G.M.D. and Clague,J.J. (2007) Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia, Canadian Journal of Earth Sciences (45) p. 549-564, doi:10.1139/E07-069

Holland, S.S., (1964) Landforms of British Columbia: A Physiographic Outline. British Columbia Department of Mines and Petroleum Resources, Bulletin (48) 138 p.

Howard, Alan D., Dietrich, William E. and Seidl, Michelle A. (1994) Modeling fluvial erosion on regional to continental scales, Journal of Geophysical Research, (99) no. B7, p. 13,971-13,986.

Kirby, Eric and Whipple, Kelin. (2001) Quantifying differential rock-uplift rates via stream profile analysis, Geology, (29) no. 5, p. 415-418.

Loget, N. and van der Dreissche, J. (2009) Wave train model for knickpoint propagation, Geomorphology (106) no. 3-4, p. 376-382, doi:10.1016/j.geomorph.2008.10.017

Matthews, W.H. (1991) Physiographic evolution of the Canadian Cordillera, Chapter 11 *in* Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath, eds., Geological Survey of Canada, Geology of Canada, no. 4, p. 403-418.

McCaffrey, R., Qamar, A.I., King, R.W., Wells, R., Khazardze, G., Williams, C.A., Stevens, C.W., Vollick, J.J., Zeick, P.C. (2007) Fault locking, block rotation and crustal deformation in the Pacific Northwest, Geophysical Journal International (169) p. 1315-1340.

Montgomery, David R. and Buffington, John M. (1997) Channel-reach morphology in mountain drainage basins, Geological Society of America Bulletin, v. 109, no. 5, p. 596-611.

Montgomery, David R. (2001) Slope distributions, threshold hillslopes, and steady state topography. American Journal of Science, v. 301, no. 4-5, p. 432-454.

Parrish, R.R. (1983) Cemozoic thermal evolution and tectonics of the Coast Mountains of British Columbia: 1. Fission track dating, apparent uplift rates, and patterns of uplift, Tectonics (2) p. 601-631.

Roering, J.J., (2008), How well can hillslope evolution models 'explain' topography? Simulating soil production and transport using high-resolution topographic data, Geological Society of America Bulletin, (120) p. 1248-1262.

Rohr, K.M.M. and Currie, L. (1997) Queen Charlotte basin and Coast Mountains: Paired belts of subsidence and uplift caused by a low-angle normal fault, Geology (25) p. 819-822.

Schildgen, T.F., Hodgges, K.V., Whipple, K.X., Reiners, P.W., Pringle, M.S. (2007) Uplift of the western margin of the Andean plateau revealed from canyon incision history, southern Peru, Geology (35) p. 523-526, doi:10.1130/G23532A.1

Seidl, Michelle A. and Dietrich, William E. (1992) The problem of channel erosion into bedrock, Functional Geomorphology; Landform Analysis and Models, Catena supplement 23, p. 101-124.

Seidl, Michelle A. (1993) *Form and process in channel incision of bedrock*. University of California at Berkeley Ph.D. thesis, Berkeley, California.

Selander, J.A. (2004) *Processes of knickpoint propagation and bedrock incision in the Oregon Coast Range.* University of Oregon B.S. thesis, Eugene, Oregon.

Sklar, Leonard and Dietrich, William. (1998) River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, *in* Tinkler, K. and Wohl, E.E., eds., Rivers over rock: Fluvial processes in bedrock channels: Washington D.C., American Geophysical Union, Geophysical Monograph 107, p. 237-260.

Stock, Jonathan D. and Montgomery, David R. (1999) Geologic constraints on bedrock river incision using the stream power law, Journal of Geophysical Research, v. 104, no. B3, p. 4983-4993.

Stumpf, A.J., Broster, B.E. and Levson, V.M. (2000) Multiphase flow of the late Wisonsinan Cordilleran ice sheet in western Canada, Geological Society of America Bulletin (112) p. 1850-1863.

Tribe, S. (2002) Geomorphic evidence for Tertiary drainage networks in the southern Coast Mountains, British Columbia, Geological Survey of Canada, Current Research 2002-A13,

Trush, W. J., S. M. McBain, and L. B. Leopold (2000), Attributes of an alluvial river and their relation to water policy and management, Proc. Natl. Acad. Sci. U. S. A., 97, 11,858–11,863, doi:10.1073/pnas.97.22.11858.

Umhoefer, P.J., Rusmore, M.E. and Woodsworth, G.J. (1994) Contrasting tectono-stratigraphy and structure in the Coast Belt near Chilko Lake, British Columbia: unrelated terranes or an arc-back-arc transect? Canadian Jounral of Earth Sciences (31) p. 1700-1713.

Ward, J.V., Tockner, K., Arscott, D.B., Claret, C. (2002) Riverine landscape diversity, Freshwater Biolog (47) p. 517-539.

Whipple, Kelin X. and Tucker, Gregory E. (1999) Dynamics of the stream-power incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs, Journal of Geophysical Research, v. 104, no. B8, p. 17.661-17,674.

Whipple, Kelin X., Hancock, Gregory S., Anderson, Robert S. (2000) River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion and cavitation, Geological Society of America Bulletin, v. 112, no. 3, p. 490-503.

Whipple, K.X. (2004) Bedrock rivers and the geomorphology of active orogens, Annual Review of Earth and Planetary Science (32) p. 151-185, doi:10.1146/annurev.earth.23.101802.120356

Wilkinson, S. N., I. D. Rutherfurd, and R. J. Keller (2008), An experimental test of whether bar instability contributes to the formation, periodicity and maintenance of pool-riffle sequences, Earth Surf. Processes Landforms, 33, 1742–1756, doi:10.1002/esp.1645.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K., and Fausch, K.D. (2010) Large in-stream wood studies: a call for common metrics, Earth Surface Processes and Landforms (35) p. 618-625, doi:10.1002/esp.1966