Chapter 1

Tectonic History of British Columbia: Historical and Current Influences on the Chilko-Chilcotin-Fraser River System

JOSHUA GARBER
DEPARTMENT OF GEOLOGY
UNIVERSITY OF CALIFORNIA, DAVIS
ONE SHIELDS AVENUE
DAVIS, CA 95616
JGARBER@UCDAVIS.EDU

ABSTRACT

The modern landscape of British Columbia is the result of hundreds of millions of years of tectonic processes, such as the prolonged subduction of oceanic lithosphere and subduction-related volcanism, the accretion of various microplates and terranes, and rapid uplift. Each of these forces has exacted long-term effects on the topography and morphology of the landscape, as is currently seen in the five "morphogeologic" belts of B.C. (e.g., Gabrielse et al, 1991; **Figure 1a**). The influence of tectonic processes on the Chilko-Chilcotin-Fraser River (CCR) system of British Columbia is particularly pronounced: as the landscape evolved, various paleo-drainages switched directions, rapidly incised and infilled older valleys, experienced rapid uplift, and interacted with voluminous volcanic and glacial deposits. Here, I analyze how the (1) large-scale and long-term tectonics and (2) smaller-scale regional geologic and geomorphologic drivers have influenced the development of the CCR system in the last 100-1 Ma. Though these processes may have only an indirect effect on local ecosystems along the modern rivers, they ultimately control the geomorphic and hydrologic landscapes of southern British Columbia. Therefore, they exert a major influence on the long-term evolution of the entire river system and the biotic systems within it.

INTRODUCTION/BACKGROUND: LARGE-SCALE BRITISH COLUMBIA TECTONICS

In the broadest sense, the geology of British Columbia is defined by the various "terranes" (after Jones et al, 1972), or exotic continental blocks, that have accreted to the edge of the North American craton. The five morphogeologic belts of B.C. (Gabrielse et al, 1991; **Figure 1a**) are defined almost exactly by boundaries between groups of accreted terranes (**Figure 1b**). As a result, these belts have different rock types, structural controls, and modern tectonic environments, which result in vastly different surface expressions. For example, the Intermontane Belt is an uplifted plateau dissected by numerous steep-walled channels, while high-relief mountains and glaciers dominate the Coast Belt.

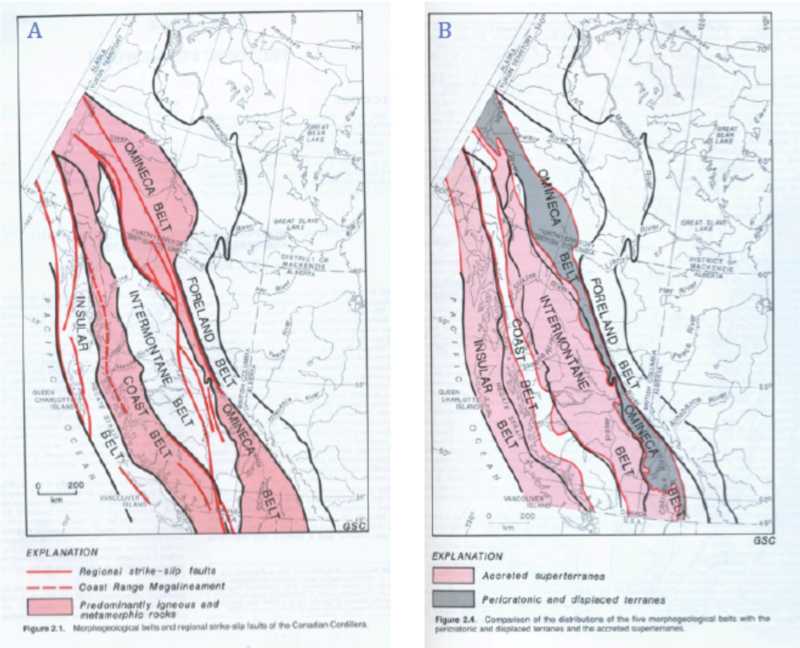


Figure 2.1. Morphogeological belts and regional strike-slip faults of the Canadian Cordillera.

Figure 2.4. Comparison of the distributions of the five morphogeological belts with the pericratonic and displaced terranes and the accreted superterranes.

Figure 1: *A*. Morphogeologic belts of British Columbia. *B*. Relationship of accreted terranes to the morphogeologic belts. (*Both figures from Gabrielse et al, 1991*)

Subsequent to their accretion, these terranes were deformed by continuing subduction and further terrane amalgamation. Changes in the direction of subduction (**Figure 2a**), however, resulted in progressive changes in the orientation of major geologic structures (**Figure 2b**). Subduction of the Farallon Plate oriented normal to the North American continental margin was active until ~50 Ma, and the various collisions produced compressional structures (e.g., fold-and-thrust belts) during the Jurassic and Cretaceous (Umhoefer and Miller, 1996, and references therein). Around 50 Ma, oblique subduction of the Kula Plate formed a set of NW-SE oriented transpressional (translation + compression) structures such as the dextral Yalakom Fault, whose main period of activity lasted from 57-44 Ma (Umhoefer and Kleinspehn, 1995; Umhoefer and Schiarizza, 1996). With the final subduction of the Kula Plate, even more oblique subduction of the Pacific Plate produced crosscutting transtensional (translation + extension) structures such as the Fraser Fault, which was active until ~34 Ma (Coleman and Parrish, 1991).

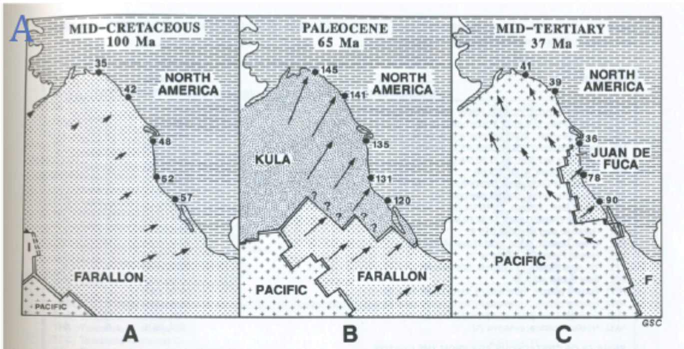


Figure 3.3. Speculative plate configuration in the mid-Cretaceous, Paleocene, and mid-Tertiary compiled from Engebretson et al. (1985). North America is fixed, and arrows give relative directions of motion of oceanic plates. Arrows lengths are proportional to velocity. Numbers show velocities (in mm/a) of oceanic plates relative to the western (fixed) margin of North America at 5 localities. I is the Izanagi Plate. The position of the boundary between the Farallon and Kula Plate is uncertain.

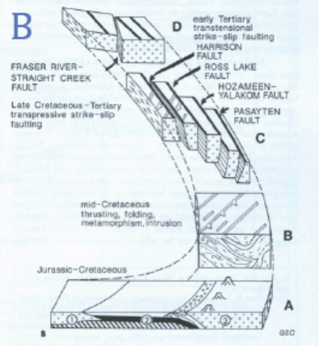


Figure 2:

A. Changes in the direction of subduction along the western margin of North America, with progressive changes in (1) the angle of convergence and (2) the oceanic plate that is being subducted. From Irving and Wynne (1991).

B. Changing orientation of major geologic structures with associated changes in the angle of convergence. From Gabrielse et al (1991).

The modern plate tectonic configuration of British Columbia is shown in **Figures 3**, **4,** and **5**. The tectonic regime in southern B.C. is dominated by continued subduction of the Juan de Fuca and Explorer Plates (remnants of the Farallon Plate), while further to the north and south the signal is dominated by dextral strike-slip

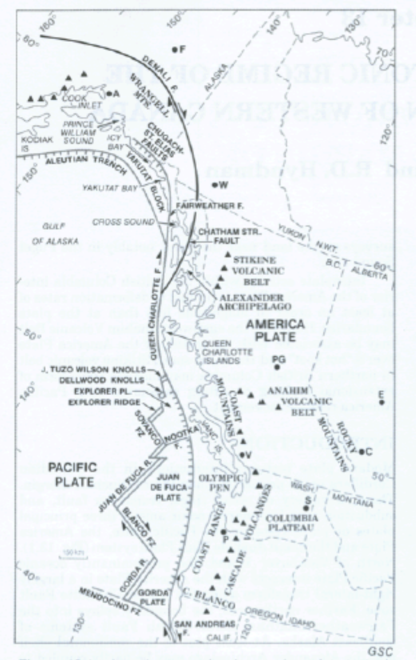


Figure 13.1. Location map showing modern plate tectonic regime of the northeast Pacific. A, Anchorage; F, Fairbanks; W, Whitehorse; PG, Prince George; V, Vancouver; P, Portland; S, Spokane; C, Calgary; E, Edmonton. Triangles represent Miocene to Recent volcanic centres.

Figure 3: Modern plate tectonic configuration of the Pacific, Juan de Fuca, Explorer, and North American plates on the western margin of North America. From Riddihough and Hyndman (1991).

motion of the Pacific Plate relative to North America (**Figure 3**). Early analyses of modern plate motions (e.g., Riddihough and Hyndman, 1991; **Figure 4**) suggested that the Pacific Plate is actually moving obliquely *away* from the North American Plate, translating northwestward at ~50-60 mm/yr. However, continued NE-SW directed convergence between the Juan de Fuca/Explorer and North American Plates is accommodated by (1) continued activity on spreading ridges between the Pacific and Juan de Fuca/Explorer plates and (2) southwestward translation of North America over the two subducting microplates (**Figure 4**). More recent work analyzing the GPS-derived deformation field (e.g., McCaffrey et al, 2007; **Figure 5**) shows evidence of counter-clockwise rotation of northern B.C. coupled with clockwise rotation of Washington and Oregon, driving nearly orthogonal convergence of the Juan de Fuca plate in southern B.C. This "straight convergence" may be partially responsible for the rapid uplift seen in southern B.C. in the last 10-1 Ma (Parrish et al, 1983), as is discussed in further detail below.

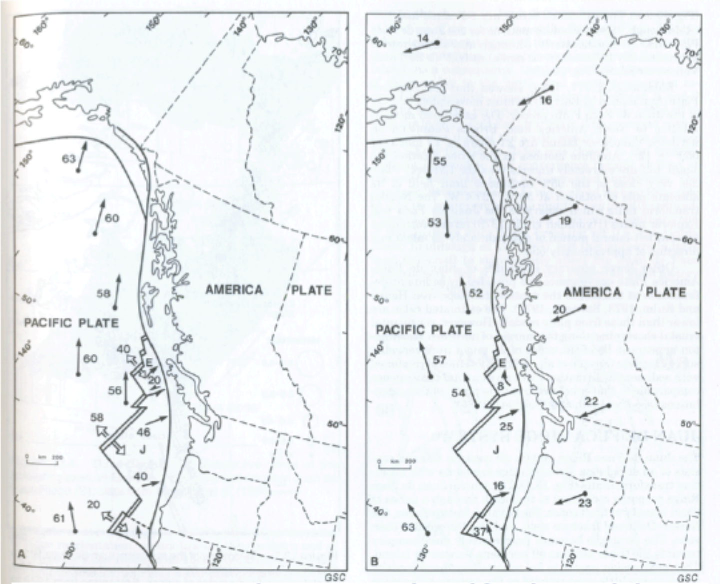


Figure 4: Contemporary plate motions, as derived from historical plate motion vector analysis. The left figure shows motion of the Pacific Plate relative to a fixed North American plate, whil the right figure shows absolute motions of Pacific and North American plates relative to a "fixed hotspot." Figure from Riddihough and Hyndman (1991).

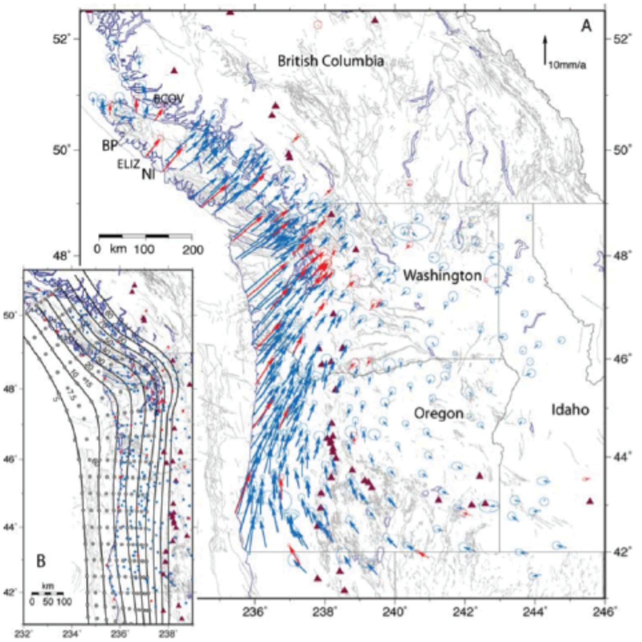


Figure 5: Modern GPS-derived plate motions in Cascadia and southern British Columbia, from McCaffrey et al (2007).

HISTORY OF THE FRASER RIVER CATCHMENT

These long-term, large-scale plate motions have had a profound influence on the development of the Chilko-Chilcotin-Fraser River system in the last 100 Ma. The dominant effect has been on changing river *base level*, or the lowest level that rivers will erode down to (or infill up to, if base level is higher than the current river stage). For example, the local base level for the Chilko River is the current elevation of the Chilcotin River, the local base level for the Chilcotin River is the current elevation of the Fraser River, and so on. (These paleo-base level changes are only recognizable because the CCR system is ancient, i.e., the current Chilko, Chilcotin, and Fraser Rivers are exploiting previous drainages that are as old as the Cretaceous.)

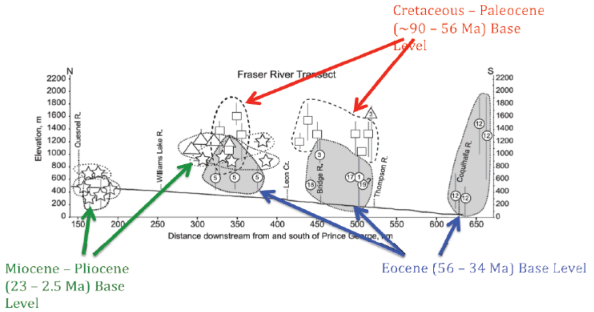


Figure 6: Changes in historical base level along the Fraser River over the last 100 Ma. Modified from Tribe (2005).

Figure 6 shows changes in the Fraser River base level during the last 100 Ma, as constrained by the elevation of fluvial deposits along the main Fraser River channel (Tribe, 2005). Cretaceous-Paleocene (~90-56 Ma) base level is now ~1700 m above the modern river channel, but Eocene (56-34 Ma) base level is very close to modern base level, suggesting a major period of uplift and incision between the Cretaceous and Eocene (Tribe, 2005). After a period of quiescence during the Oligocene with little deposition of new material, Miocene and Pliocene (23-2.5 Ma) base levels along the Fraser River overlie Eocene deposits, suggesting a period of tectonic subsidence and infilling of formerly incised channels (Tribe, 2005). Recent uplift and glaciation since 4 Ma have led to another period of active stream erosion (Parrish, 1983; Mathews, 1989); modern rivers in southern B.C. have re-exploited older channels, producing a "peneplain", or uplifted plateau with narrow, deeply incised channels. While shorter-term and smaller-scale processes have also had a major influence on the evolution of the CCR system, these broad but relatively rapid changes in river base level have been the most consequential for determining changes in river provenance and drainage direction.

Summarizing various sources focusing on sedimentary deposits, tectonic uplift, changes in plate motions, and volcanic deposits, an integrated geologic and tectonic history of the CCR system can be developed for the past 60 Ma:

(1) During the late Paleocene and Early Eocene (60-45 Ma), the Coast Ranges experienced a period of major tectonic uplift (Parrish, 1983). This broadly coincides with the transition from transpression to transtension along the Pacific-North American plate boundary (Umhoefer and Schiarizza, 1996). The tectonic uplift associated with this shift led to hundreds of meters of incision (Tribe, 2005), significant and large-scale erosion of Cretaceous and Paleocene strata (Parrish, 1983), and produced highlands in the southern Coast Ranges (Tribe, 2005). This period coincides with a *northward*-draining Fraser River system (Tribe, 2005); it is likely that the southern Coast Ranges acted as a drainage divide.

(2) During the mid- to late Eocene (~45-34 Ma), uplift apparently ceased, leading to deposition and restricted infilling of incised river valleys (Tribe, 2005). Paleoflow indicators (ripples, dunes, imbrication, etc.) from these sedimentary deposits show

evidence for clear northward transport along proto-Fraser and proto-Chilcotin Rivers (Tribe, 2005, and references therein).

(3) The Oligocene to early Miocene (34-20 Ma) was marked by very low rates of tectonic uplift (Parrish, 1983; Farley et al, 2001) and there are few sedimentary deposits of this age along the Chilko, Chilcotin, and Fraser Rivers. However, the Coast Ranges experienced a major reduction in topography by the Miocene (e.g., Mathews, 1991), suggesting that the Coast Ranges ceased to be a topographic high during this period.

(4) The Miocene-Pliocene (20-1 Ma) history of the Chilko-Chilcotin-Fraser system is dominated by the periodic eruption and deposition of Chilcotin Group basalts (Bevier, 1983; Mathews, 1989). These "plateau basalts" were produced by back-arc extension, as the overriding North American Plate moved southwestward over the subducting Juan de Fuca Plate and caused localized extension east of the main volcanic arc (**Figure 7**). Though these basalts produce only a thin mantle (<25 m) across most of the landscape (Mathews, 1989; Mihalynuk, 2007), numerous observations and a recent thickness model show that the Chilcotin Group can be >300 m thick in large paleochannels that mimic the modern Chilko-Chilcotin-Fraser drainage system (Mathews, 1989; Mihalynuk, 2007; **Figure 8**). Additionally, there are wide, uplifted paleochannels infilled by subaqueous Chilcotin Group basalts along modern river drainages (e.g., Gordee et al, 2007). Finally, the top of the Chilcotin Group basalts slope gently down towards the modern Chilko, Chilcotin, and Fraser Rivers (Mathews, 1989). All of these observations strongly suggest that the CCR drainage system was active prior to the deposition of the Chilcotin Group (i.e., before 20 Ma), during volcanism (20-1 Ma), and even outlasted volcanic deposition until today (<1 Ma). However, drainage direction for the Fraser-Chilcotin part of the system appears to have been northward for most of this time period (Mathews and Rouse, 1984, 1986; Tribe, 2002).

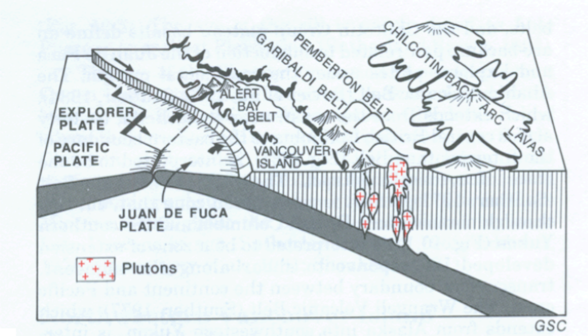


Figure 7: Tectonic setting of the Chilcotin Group extensional basalts relative to the subducting plate and volcanic arc. From Souther and Yorath (1991).

(5) The geologic history of the CCR system from 10-1 Ma deserves special mention. Coinciding with the onset of major glaciations (Farley et al, 2001) and changes in Pacific Plate motions (Atwater and Stock, 1998), southern British Columbia experienced a major period of tectonic uplift, northward tilting, glacial deposition, and riverine incision during this time period, with most uplift focused from 4-1 Ma (Parrish, 1983; Mathews, 1989; Farley et al, 2001). Though it is not clear exactly when it occurred, this time period saw the reversal of the Fraser River from northward to southward-draining (Mathews and Rouse, 1984, 1986; Tribe, 2002, 2005). This reversal was driven by up to 3.5 km of uplift in the southern Coast Ranges (Parrish, 1983; Farley et al, 2001), as a southward-draining proto-Fraser River in the south (from Hope to Vancouver) eroded northward, while a northward-draining proto-Fraser River further to the north simultaneously incised southward.

> These two streams probably met and established a southward-directed flow near the Hell's Gate fish ladder, which is the narrowest part of the modern Fraser River and likely acted as a drainage divide (Tribe, 2003). There, the Fraser River has cut through Tertiary and Quaternary sediments (Tribe, 2003), suggesting that the development of the entire southward-draining system may be as young as Pleistocene, perhaps influenced by glaciers (Mathews and Rouse, 1984; Farley et al, 2001). However, other geomorphic evidence suggests that the system may have drained southward after ~15-10 Ma (Tribe, 2002). Uncertainty in this value complicates the history of the CCR system, but the main point is that the north-draining proto-Fraser River system (and by association the Chilcotin River) must have changed course in geologically recent time (15-1 Ma). (The Chilko River, though poorly studied, is not expected to have changed course; it is still north flowing today.)

One major unresolved question is the driving force behind the modern tectonic uplift of the southern Coast Ranges that forced changes in drainage direction. This uplift may approach 0.6 km/Ma (6 mm/yr) in the last 4-5 Ma (Parrish, 1983). Though it is still debated, various authors have suggested the influence of extension in the Queen Charlotte Basin to the north (Rohr and Currie, 1997), changes in Pacific Plate motions (Parrish, 1983; Atwater and Stock, 1998), steepening of subduction (Parrish, 1983), or glacial influence (Farley et al, 2001). It can also be suggested that the increasing influence of North American Plate rotation (e.g., McCaffrey et al, 2007) may have directed convergence toward the southern Coast Ranges, as is seen in the oroclinal bend of the Andes (e.g., Isacks, 1988). This increasing convergence also coincides with a southward shift in uplift with time along the axis of the Coast Range (Parrish, 1983).

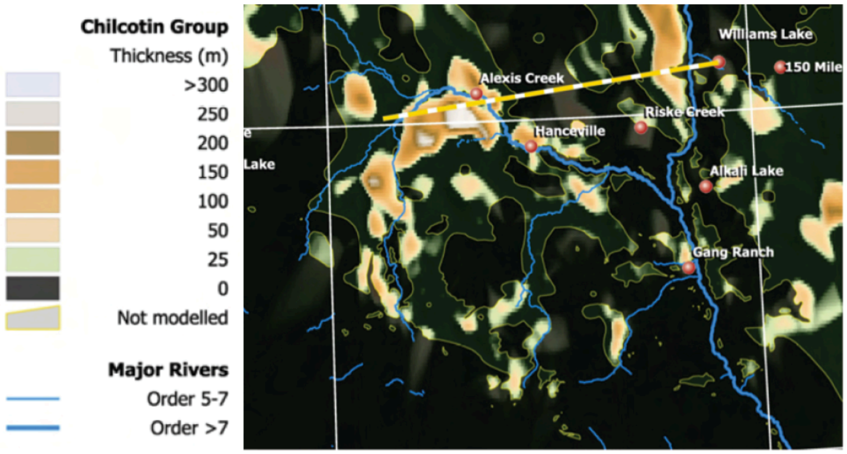


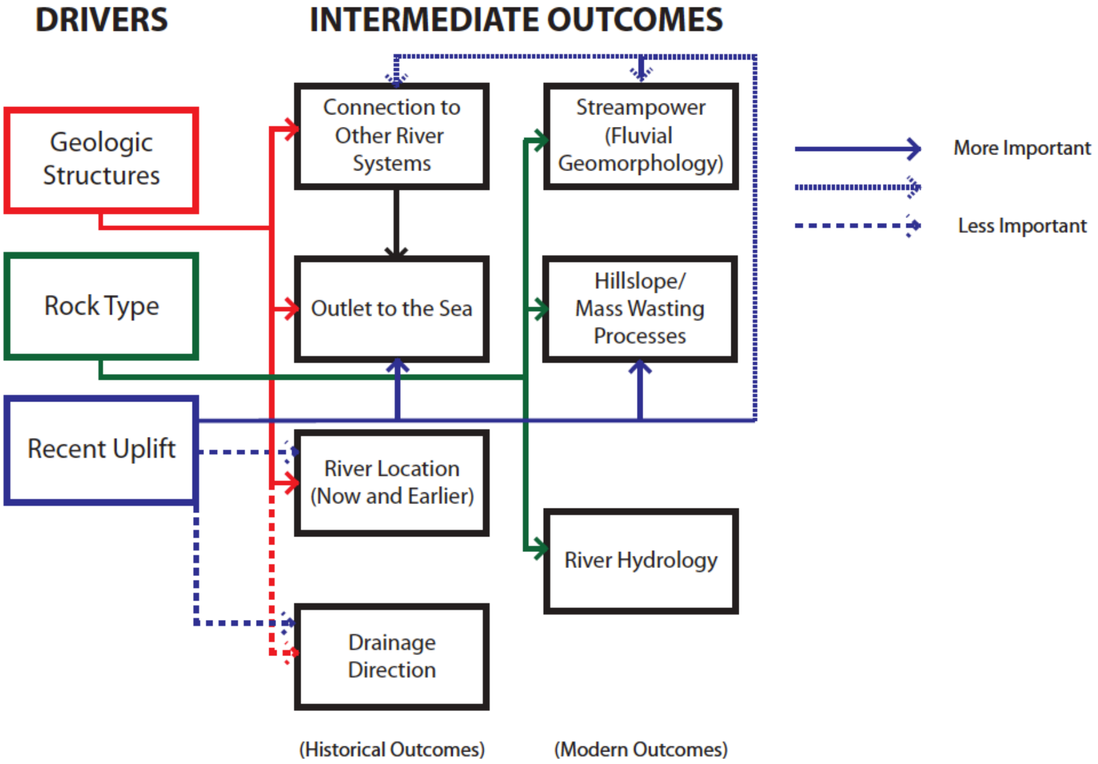
Figure 8: Thickness model for the Chilcotin Group basalts along the Chilko, Taseko, Chilcotin, and Fraser Rivers. Note the very large thickness of basalt along modern channels, suggesting that these channels inhabit much older drainage systems that have been active since at least 20 Ma. From Mihalynuk (2007).

While uplift in the Coast Ranges has been well studied, tectonic uplift in the Intermontane Belt is poorly constrained (Andrews et al, 2007, 2009). However, there is abundant evidence for recent uplift (steep-walled drainages, perched abandoned drainages, immature sedimentary deposits) that elucidate the need for more quantitative work (Andrews et al, 2007, 2009).

Bedrock Geology along the CCR System. A geologic map of the CCR system is shown in **Figure 9**. Chilko Lake is seated in a tectonic collage of volcanic, intrusive, metamorphic, and sedimentary rocks of dominantly Mesozoic age (Cadwallader and Stikinia terranes: Umhoefer et al, 1994) in the high-relief Coast Belt. The Chilko River exits the lake and crosses the Yalakom Fault into glacial sediment and eventually hits Chilcotin Group basalts (Bevier, 1983) at Lava Canyon. Through its confluence with the Taseko, and eventually its join with the Chilcotin River, the main channel variably cuts into basalts or glacial material; as the Chilcotin approaches and joins the Fraser River, it cuts through a small section of Cache Creek terrane (metamorphic rocks).

Figure 9: Geologic map of the CCR system, from the Geological Survey of British Columbia. The various rock types along the CCR system are described in the text.

THE MODEL



The various effects of tectonic processes on the Chilko-Chilcotin-Fraser system are shown above. Three main tectonic "drivers" have been identified that affect the CCR system:

(1) Geologic Structures: these are relatively well constrained, and include the Fraser and Yalakom Faults. Both the Yalakom and Fraser Faults play a major role in the CCR system today; the Yalakom Fault serves as the eastern mountain-front fault for the Coast Ranges and separates the Coast and Intermontane Belts, while the Fraser River follows the Fraser Fault for much of its trace. Though there was a >10 Ma delay between the end of activity on the Fraser Fault and the development of the Fraser River (Tribe, 2002), the Fraser Fault may have also acted as a conduit for the rise of deep, formerly meteoric waters (Jones et al, 1992, and references therein) along its trace.

(2) Rock Type: this too is well constrained, and has been described above along different parts of the CCR system.

(3) Recent Uplift: this is the most relevant tectonic driver, and the least well constrained, especially in the Intermontane Belt. Climatic and glacial influences can have an effect on this driver (e.g., Molnar and England, 1990).

These drivers affect a set of “historical outcomes” (outcomes that affected the development of the drainages) and “modern outcomes” (those that affect the drainages today). Historical outcomes are as follows:

(1) *Connection to Other River Systems*. The external connections of the CCR system, such as a possible connection to the Stikine River further north, have been mostly affected by activity along major geologic structures, which directly affects topographic restrictions on drainage patterns. However, recent uplift has also affected connections between river systems, such as between the two proto-Fraser Rivers that eventually joined together. This historical outcome is expected to have a major effect on modern faunal and floral assemblages on the CCF system.

(2) *Outlet to the Sea*. The same factors affect this outcome as above, but connections to other river systems also have also determined where the Chilko-Chilcotin-Fraser system has drained into the ocean. (I have not found any literature discussing where the northward proto-Fraser River would have met the sea.)

(3) *River Location (Now and Earlier)*. This outcome is affected by activity along major geologic structures (such as the Fraser River along the Fraser Fault) and recent tectonic uplift, which develops new drainages and diverts older ones.

(4) *Drainage Direction*. The direction of major drainages has been most strongly affect by recent uplift, which changed the course of the Fraser River over the last 15-1 Ma. However, activity along geologic structures such as the Fraser Fault may have also affected the historic drainage direction of the Chilko, Chilcotin, Fraser, and other southern B.C. rivers.

Three modern outcomes are affected by these drivers: streampower (a proxy for fluvial geomorphology), hillslope and mass wasting processes, and river hydrology. Streampower and hillslope processes are both affected by both rock type (especially differences in erosivity) and recent uplift, while river hydrology is only affected by rock type. Broadly, these three modern outcomes can be grouped as (1) geomorphic or (2) hydrologic processes, which are discussed in detail by Selander (this volume) and Burley (this volume).

Tectonic processes, then, are most relevant on a catchment or regional scale, and are at least a few steps removed from ecosystem-level processes such as habitat formation and trophic interactions. However, while tectonics does not directly affect local ecosystems, these forces can still cause long-term changes to the landscape that force a response from biotic systems, which are described further by numerous other papers in this volume.

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