Geologic Controls on Physical Habitat Distribution, Grande Ronde River, Oregon and Washington

by Dylan J. Caldwell

ABSTRACT

The Grande Ronde River, and its associated watershed, flows through a region in northeastern Oregon, which has experienced a dynamic geologic history. During Mesozoic times, the granitic Wallowa Pluton intruded into the area. Approximately 17.5 Ma (million years ago), during Miocene times, the eruption of the Columbia River Basalt Group commenced and proceeded for another 11.5 million years. These flood basalts and associated tectonic events drastically changed the surrounding terrain. Significant amounts of uplift continued after the basaltic eruptions and caused local river systems to develop antecedent features that flow through distinctly different rock types. The River Continuum Concept (Vannote et al. 1980) may provide a basis for understanding the gradational changes of ecological habitats seen in the Grande Ronde River system. However, due to the geologic complexity of the area, the Process Domain Concept (Montgomery 1999) may prove more applicable for understanding the distribution of physical habitat and ecosystem function in this locality.

INTRODUCTION

Seventeen million years ago, flood basalts, now known as The Columbia River Basalt Group (CRBG), erupted over areas in Washington, Oregon, and Idaho. Prior to the eruptions of the CRBG, during late Jurassic/early Cretaceous times, this same area in the northwestern U.S. experienced the intrusion of a large pluton (see next section for further description), followed by 6 million years of significant tectonic uplift. The diverse geologic history in this area has had significant impacts in the surrounding watersheds. Stream and rivers in the area, such as the Minam, Wallowa, and Grande Ronde, are characterized by alpine headwaters that transition into deep basaltic gorges and canyons. This combination of physical characteristics has a large impact on the stream morphologies and the subsequent ecological communities. Due to the significant influence of the diverse geology, its is likely that the rivers poorly represent a continuum as described by the River Continuum Concept (RCC) and are better described by the Process Domain Concept (PDC) (Hestir 2007, this volume).

REGIONAL GEOLOGIC HISTORY

To understand how geologic structures and geomorphic processes influence the distribution of physical habitat within the Grande Ronde River basin, a detailed geologic history of the study region in the northwestern United States must be presented. Thus, the regional geology of pre-flood basalt activity is discussed as well as a general description of the basaltic magmas, a probable process by which the CRBG was erupted, and the following tectonic uplift.

Mesozoic Tectonics

During Mesozoic times (248-65 Ma), the primitive oceanic crust of the Farallon plate was subducting beneath the western continental margin of the North American Plate (Fig. 1). During these times, the paleo-continental margin was much farther inland compared to the existing margin, located approximately in present-day western Idaho (Fig. 2) (Hales et al. 2005). The subduction zone located offshore and west of the Mesozoic continental margin had many influences on the regional geology of the western United States. Subduction related arc volcanism processes resulted in the formation of the Cascade Range volcanoes still seen today (i.e. Mt. Shasta, Mt. Hood, Mt. Jefferson, Mt. St. Helens, Mt Rainier), while concurrent tectonic plate movements allowed many oceanic terranes to accrete onto the paleo-shore of the western continental margin.

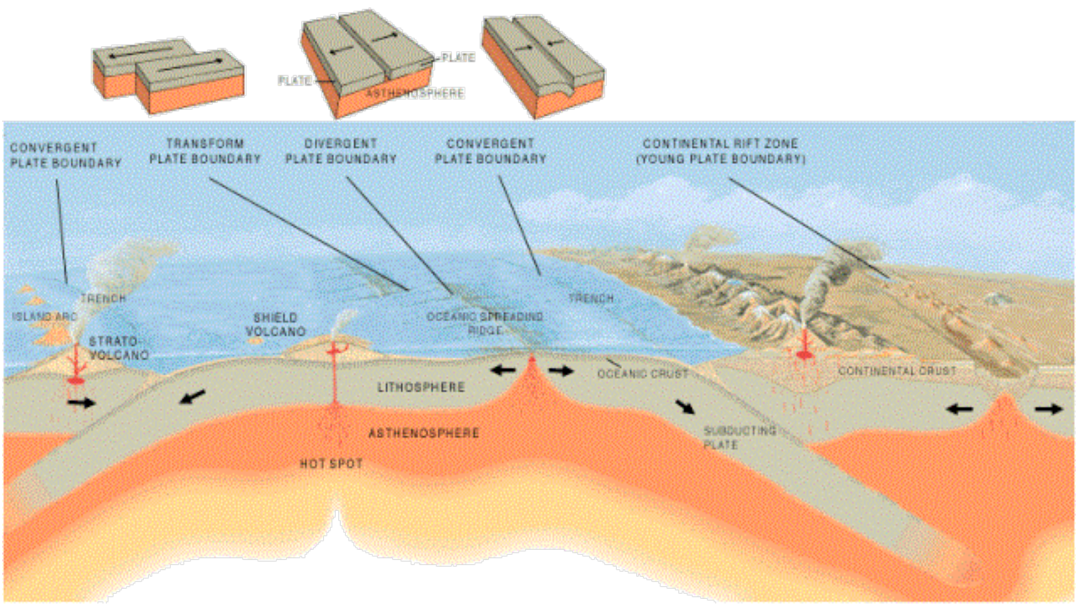

Figure 1. Diagram showing subduction zone and related tectonic processes. (USGS 2007)

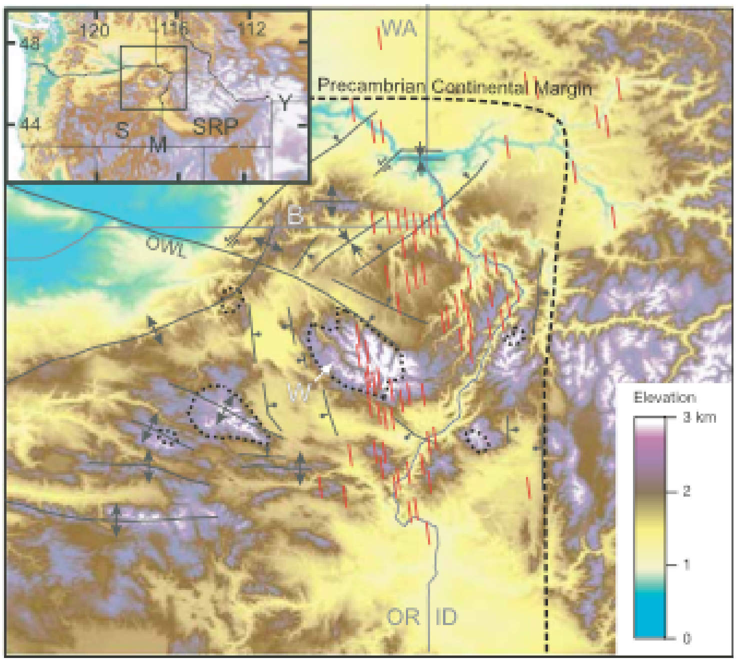

Figure 2. Map of regional geologic structures and the approximate location of paleo-continental margin. (Hales et al. 2005)

Collisional processes at this convergent plate boundary (Fig. 1) caused extensive structural deformation of rocks located on the continental margin. Low-lying back-arc extensional zones were also formed behind the volcanic front in the region occupied by the present day Grande Ronde River Basin. A large, shallow inland sea occupied this then low-lying area, and over time, large volumes of oceanic sediments accumulated of the inland sea floor, only to be metamorphosed (deformed and recrystallized) under the heat and pressure associated with subsequent tectonic activity including the intrusion of the Wallowa Pluton (Fig. 2). Remnants of these marine sediments can still be seen today as metamorphosed rocks in the Wallowa Mountains (Orr et al. 1992).

In the late Jurassic/early Cretaceous (160 – 100 Ma), large igneous plutons (rock bodies that slowly crystallize below the surface and are subsequently exposed through uplift and erosion) intruded into the area (Winter 2001). The largest pluton in the area, identified as the Wallowa Pluton, has a granitic-like composition, and forms the bulk of the Wallowa Mountains seen today (the high-elevation area in the center of Fig. 2).

Miocene Tectonics and Flood Basalt Emplacement

Columbia River Flood Basalt Eruptions

The CRBG was sourced directly from the mantle. These basalts have very primitive compositions that are rich in Mg and Ca, and depleted in Si, K, and Na, which causes the rocks to have a grey – black color (Fig. 3). The CRBG is primarily fine-grained and aphyric (lacking distinctly larger crystals). Like most basaltic magmas, the CRBG had a very low viscosity when it erupted. This characteristic of basalts leads them to flood (Fig. 4), instead of explode, as expected in the more "traditional" volcanic eruption.

Figure 3. A basaltic rock. (USGS 2007)

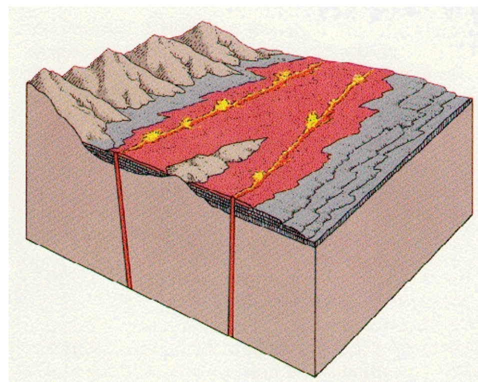

Figure 4. 3-dimensional diagram of flood-basalt eruption. (USGS 2007)

The lava that composes the CRBG was erupted through a system of fissures, which are located across the Oregon, Washington, Idaho tri-state area (Fig. 5). A fissure is a long and narrow separation in the Earth's crust that may act as a conduit for sub-surface magmas to reach the surface. Although fissures in general may be smaller, the fissures involved in the CRBG are 10's – 100's of miles long. Due to the sheer magnitude of the CRBG, it is not unexpected that the associated fissures are of such a large scale. When the magmas reached the surface, via fissure, they then spread out laterally, inundating the existing terrain, and were regulated spatially by the regional topography. The ancestral valleys and river channels were filled, erasing any existing drainage networks (Camp & Hooper 1981).

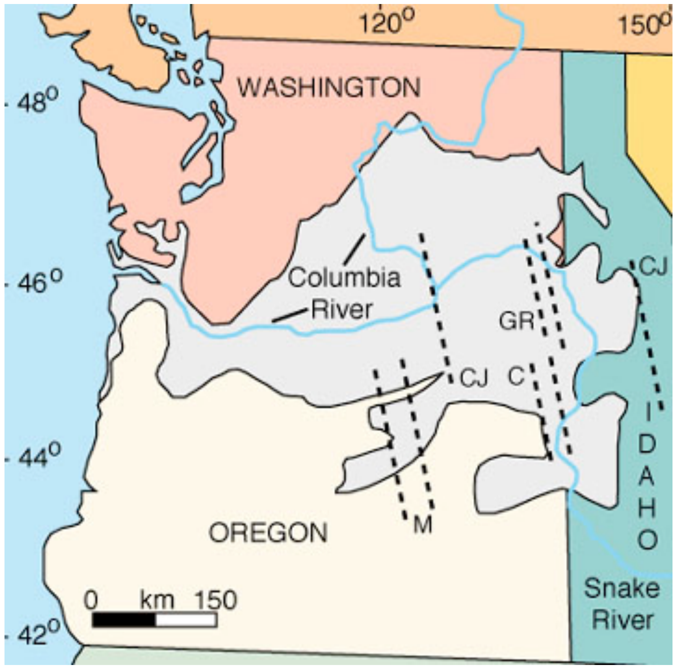

Figure 5. Map showing extent of CRBG (grey) and locations of fissures (dotted lines). (USGS 2007)

The source of the magmas in the CRBG has been directly correlated to the activity of the existing Yellowstone hotspot (Hales et al. 2005). A hotspot is a single location in the Earth where molten magma from the mantle is able to reach the surface, in a confined narrow region, and erupt. Such volcanic archipelagos as the Hawaiian Islands, the Galapagos, and the Azores are products of hotspot activity. Furthermore, hotspots may also be located underneath continents, as is the case in present-day Yellowstone National Park.

Timing and Morphology of the Columbia River Basalt Group

Starting 17.5 Ma, eruption of the CRBG commenced and progressed until 6 Ma. During the 11.5 million years of eruptions, an approximated total of 56,000 Miles^3 (234,000 km^3) of basaltic lava was evacuated onto the continental surface, covering areas in Oregon, Washington, and Idaho (Fig. 5). Individual flows were as large as 500 to over 700 Miles^3 (2000 – 3000 Km^3) making them the largest known terrestrial lava flows (Winter 2001). The average thickness of flows was 65 – 260 ft (20 – 80 m), but thicknesses up to 500 ft (150m) are also seen where lava filled in low-lying depressions (Winter 2001). In 1.5 million years, from 17.0 – 15.5 Ma, approximately 87% of the total flow volume was erupted in what is known as the Grande Ronde

Basalt (discussed more below). All flows contained remarkable compositional homogeneity throughout their extent, suggesting that there was little magmatic differentiation or chemical zoning in the presumed massive magma chamber(s) (Winter 2001). Some of the largest flows, which are associated with the Grande Ronde Basalts, flowed from their source location in northeastern Oregon/southeastern Washington over 250 miles (400 km) to the paleo-shore of the Pacific Ocean and were deposited on the continental margin (Winter 2001).

Although the CRBG consists of five different sub-groups, the Grande Ronde Basalts (GRB) sub-group, which composes approximately 87% of the total flows (Fig. 6), is comprised of approximately 35 individual flows, and represents 2,600 stratigraphic feet (800 m) of the CRBG sequence. The GRB are distinguished by texture, mineralogy, and major element composition. Sourced from the Cornucopia and Grande Ronde dike swarms, designated C and GR, respectively, in Figure 5, the GRB were the center of volcanic activity during their time. The GRB itself is separated into 4 magnetostratigraphic units, R_1, N_1, R_2, and N_2. R and N refer to the "reverse" and "normal" polarities of the Earth's paleomagnetic field, respectively. At a large enough time scale, the magnetic polarity of the Earth will switch back-and-forth between the North and South Pole. At present, we are in a phase of "normal" polarity. The GRB represents two complete cycles of the Earth's alternating magnetic polarity, which is recognized in rocks through the alignment of magnetized minerals that align themselves in specific directions (depending on the current polarity) during crystallization.

Syn-eruptive tectonics and deformation

During times of flood basalt eruption, movement along the Limekiln Fault caused uplift in the Joseph Plains and Nez Perce Plateau (Fig. 7). The westward tilting created by this uplift caused basalt flows to pinch out in the east (the area of uplift) and flow to the west, as seen in the cross-section in Figure 7.

Since the initiation of the basaltic eruptions, the southeast of the Columbia Plateau has undergone over 6500 ft (2000 m) of uplift. The causes for this immense uplift are separated into two distinct processes. During the 11.5 million years of eruptions, there was approximately 650 -1000 ft (200-300 m) of uplift (Hales et al. 2005). This syn-eruptive uplift is associated with the depletion of 56,000 miles^3 of dense basaltic magma from the mantle. The mantle becomes relatively more buoyant when the dense magma is evacuated and spread across the surface of the continent. The result is a simultaneous uplifting in the area of mantle depletion.

Stratigraphic Subdivision of Columbia River Basalt Group (CRBG)

SERIES		GROUP	SUB-GROUP	FORMATION (Age, Volume, % of CRBG)	MEMBER	MAG*
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt SubGroup	Saddle Mountain Basalt (14-6 Ma, 2,400 km3 volume, 1.5% of CRBG)	Lower Monumental Member	N
					Ice Harbor Member	N,R
					Buford Member	R
	Middle				Elephant Mountain Member	R,T
					Pomona Member	R
					Esquatzel Member	N
					Weissenfels Ridge Member	N
					Asotin Member	N
					Wilbur Creek Member	N
					Umatilla Member	N
				Wanapum Basalt (15.5-14.5 Ma, 10,800 km3 volume, 6.0& of CRBG)	Priest Rapids Member	R3
					Roza Member	T,R
					Frenchman Springs Member	N2
					Eckler Mountain Member	N2
				Grande Ronde Basalt (17-15.5 Ma, 151,700 km3, 87%)		N2
	Lower					R2
				Picture Gorge Basalt		N1
						R1
				Imnaha Basalt (17.5-17 Ma, 9,500 km3 volume, 5.5% of CRBG)		R1
						T
						N0
						R0

* Magnetic Polarity:
N, normal; R, reversed; T, transitional; subscripts denote magnetostratigraphic units

USGS Topinka, USGS/CVO, 1997, Modified from: Swanson, et.al., 1989, AGU Field Trip Guidebook T106

Figure 6. Stratigraphic column showing the individual units of the CRBG. (USGS 2007)

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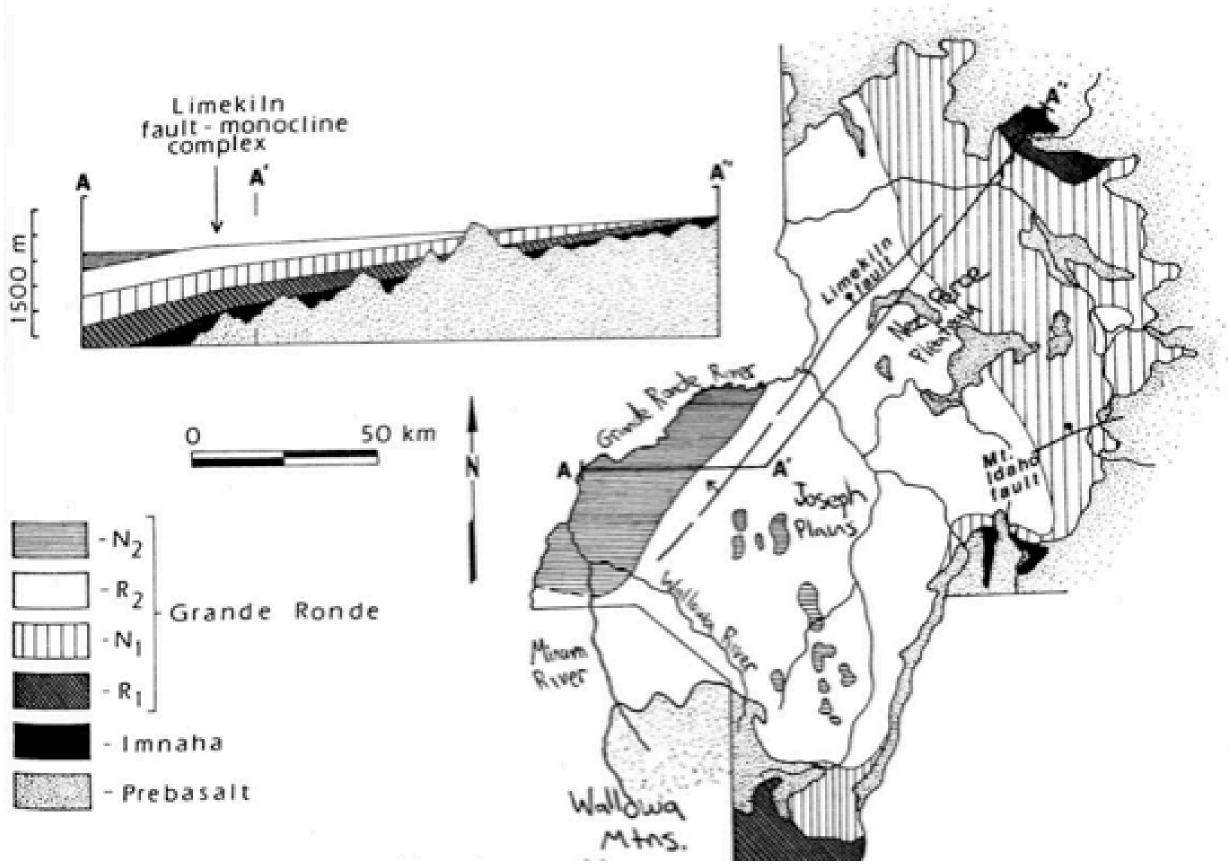

Figure 7. Map view and cross-section of the southeast part of the Columbia River Basalt Group immediately after eruption of Grande Ronde Basalt. (modified from Camp & Hooper 1981)

However, this mantle depletion model cannot account for the more than 6500 ft. of uplift that the area has experienced. The majority of the uplift has been attributed to a more complex process. Hales et al. (2005) have proposed a model that can account for the additional 5500-6000 ft of uplift. In their model, they propose that the significant uplift is due to the convective separation of the Wallowa pluton's dense roots. The delamination of the crustal exposure from the deep roots causes the area to become more buoyant again and uplift to a much higher magnitude. Such an event is strongly supported by the bull's-eye pattern of uplift centered on the Wallowa pluton (Hales et al. 2005) (Fig. 2).

In the time directly after the eruptions of the CRBG, a primitive paleo-Grand Ronde River channel was likely in the stages of forming. The area still remained relatively flat at this time since the majority of uplift in the area had not yet occurred. These relatively "young", low-gradient rivers likely had meandering channels that were developing in the newly formed soils on top of the flood basalts. These early-stage meanders are still visible in the river today. As the surrounding plateau consistently rose in elevation, the meandering river channel slowly incised into the underlying basalts (Baldwin 1964). The rising plateau created more slope on the channel, which leads to incision, and likely initiated a meandering pattern to counteract the increased flow velocity. All of the major rivers (Snake, Salmon, Imnaha, Grande Ronde, and Clearwater River) in the surrounding Columbia Plateau area demonstrate an incising river's immense power by eroding the bedrock into gorges and canyons. In the case of the Grande Ronde River, the highly resistant basalts prevented the river meanders from straightening and essentially locked them in place. The Grande Ronde River, and its incised meanders are thus antecedent features (Fig. 8).

Figure 8. Aerial photo of Grande Ronde River through a flood-basalt canyon. (Jensen 2007)

Pleistocene Glaciation

During the Pleistocene Epoch, approximately 2 Ma to 11,000 Ka, glaciation became the most prominent landscape-changing force in northeastern Oregon. Unlike the most northern latitudes of the United States, which were covered in massive ice sheets, northern Oregon only had glaciers in the high valleys of its mountain ranges, with the peaks and ridges of the mountains remaining above the ice (Baldwin 1964). The glacial carved mountains in the Wallowa's have caused them to be referred to as the Oregon Alps (Orr et al. 1992). During glacial times, the Wallowa's contained nine large glaciers that each spanned more than 10 miles, several of which were over 20 miles (the Lostine, Minam, and Imnaha). Average thickness of the glaciers was around 1000 ft. but was as much as 2,500 ft in the Lostine Glacier (Orr et al. 1992). The last recorded glacier in the Wallowa's was documented in 1929 on the ridge above Glacier Lake, at 800 ft long, 60 feet wide, and 24 feet thick (Orr et al. 1992).

Glaciers are one of the most erosive forces on the Earth and are capable of producing mega-lithic structures, such as Half Dome in Yosemite National Park. The high Wallowa's are riddled with glacial cut structures. At the head of a glacier there is usually an accumulation zone where the ice scours out a deep depression and, once melted, forms an alpine lake, known as a cirque lake. Glaciers also shape the bedrock and can produce substantial cliff faces (Fig. 9). When a mountain glacier leaves its valley and stretches out into lower elevations, it generally terminates. Much like rivers, glaciers flow through their valleys, just at a much slower rate. The incredible friction caused by the glacier scraping over underlying rock produces vast quantities of sediments, known as till. This till is then carried down-valley with the glacier and is deposited in the lower reaches. Large accumulations of this glacial till are known as moraines. When the till is deposited on the sides of the glacier it forms and lateral moraine, and when it is deposited at the end of the glacier it forms and terminal moraine. There are also medial moraines that form in the center of a glacier and are sourced from the two inside lateral moraines at a confluence between two glaciers. A text-book example of lateral and terminal moraines can be seen in Wallowa Lake (Fig. 10). The moraines form natural boundaries that enclose the mountain runoff and create a lake.

Figure 9. Glacial-cut face and cirque lake in the high Wallowas. (Jensen 2007)

Figure 10. Lake Wallowa, enclosed by lateral and terminal moraines. (Jensen 2007)

Glaciation in the Wallowa's also contributed to many depositional and geomorphologic changes in the surrounding river basins. Pleistocene floodplains and terraces were formed from the large amounts of sediments being transported through the rivers. These geomorphic features can be seen today and may help form habitats for riparian biota (Stewart 2007, this volume). The surrounding geology may also govern the probability of formation of such floodplains and terraces. For example, along reaches of the Grande Ronde that flow through the large basalt canyons, it is not as likely that large floodplains or terraces will form due to the steep rock walls. The opposite is true in reaches where the river flows through areas with lower topographic relief.

GEOLOGIC INFLUENCES ON CHANNEL FORM AND HABITAT

The River Continuum Concept

From an aquatic ecology and Leopoldian geomorphology (Leopold and Maddock 1953) perspective, there is a continuous gradient in physical variables and structures in rivers, creating a physical template for corresponding biological communities. This general model, described as the River Continuum Concept (RCC), was first presented by Vannote et al. (1980) and is discussed in detail Hestir (2007, this volume).

When viewed at a large enough scale, the RCC provides a conceptual model useful in understanding observed longitudinal gradients of physical habitat features in river systems. The Grande Ronde River, although unique, may be explained by the RCC. The river begins as a series of high alpine streams that descend in elevation and accumulate into higher order streams in the middle reaches (e.g. in the confluence of the Wallowa and Grande Ronde Rivers). These middle reaches then flow through deeply incised basalt gorges and eventually confluence with the much larger Snake River. This progression can be thought of as a balance of energy. In the headwaters, where there is high slope and relatively less channelized water, there is an abundance of potential energy. With further distance downstream potential energy is converted to kinetic energy, seen in significantly larger volumes of moving water (Leopold and Maddock 1953).

An example from the Grande Ronde River that may be described by the RCC is the distribution of particular sediments in the river channel and riparian habitats. The numerous rivers and creeks that descend from the Wallowa Mountains into the Grande Ronde River experience a significant transition in the bedrock types through which they flow. As discussed earlier, the Wallowa's are primarily composed of the granitic-like Wallowa Pluton. This rock composition differs greatly from that of the basalts, which composes most of the terrain that the Grande Ronde River flows through. Due to erosion of the Wallowa Pluton in the higher mountain reaches, much of the transported material will be granitic-like as well. Once the river reaches the basalts, this rock type will be eroded into transported sediments. The transition will not be as distinct as the contact in the rocks, since the river provides a means of transportation for entrained sediments and other particles. Instead, there will be a transition zone that represents a continuum. The transported and riparian sediments will still likely be dominantly granitic-like at the granite – basalt contact, but with further distance downstream, the granite-like sediments will become less prevalent, and the basaltic sediments will dominate.

Changes in geologic structure will influence the RCC and the associated predictions based on this concept. In areas that have a more stable climate, gentle topography, and simple geology, the RCC may provide a more accurate and realistic conceptual model (Montgomery 1999). In this regime of more simplistic physical parameters, river characteristics such as channel size and organic matter retention may be explained as a continuum that has gradational changes. However, in the case of the Grande Ronde and other adjacent systems, there exists variable climate, steep topography, and complex geology. As discussed by Montgomery (1999) this scenario may be better explained by the Process Domain Concept.

The Process Domain Concept

The Process Domain Concept, introduced by Montgomery (1999), is said to be an alternative to the RCC in that it looks at geomorphic processes and how they interact with aquatic ecosystems (Hestir 2007, this volume). Specifically, the PDC looks at the reach or valley segment scale and classifies certain domains based on the distinct physical processes that characterize them. The concept seems to rely significantly on the influence of geomorphic processes to river ecosystems/habitats, which makes it particularly useful to rivers such as the Grande Ronde, which contains varying physical characteristics. In Figure 11, the PDC is roughly illustrated at a river system scale, and shows how physical/geomorphic processes segment the river into different domains. The concept can be further divided into even smaller "process domains" that are characterized by particular physical constraints. In the case of the Grande Ronde River, which contains a multitude of differing physical (i.e. geologic/geomorphic) characteristics, the PDC can provide a workable basis for separating the river into distinct areas, or "domains."

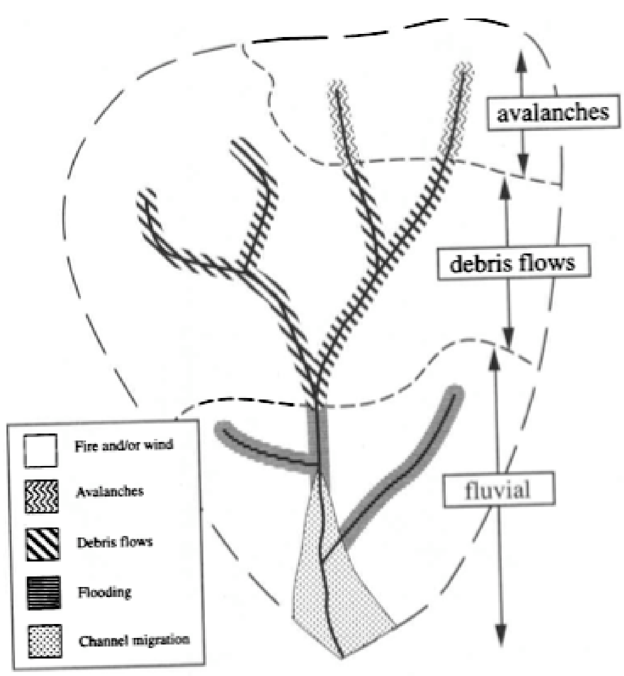

Figure 11. Coarse-scale riverine process domains in a Pacific Northwest watershed. (Montgomery 1999)

The upper tributaries to the Grande Ronde can be viewed as a “process domain” that is identified by its high slopes and granitic bedrock. In these reaches you could predict that relatively small Pleistocene terraces would be present in riparian areas providing a significant canopy to the river. In upper reaches there is less channelized water so channel cross-sections will likely have high width-to-depth ratios. In the middle reaches there is the unique basalt gorge and antecedent meanders. Here, where valley walls are very steep, Pleistocene terraces or floodplains will not be significantly large since there is not as much room for such depositional features to develop. Individual meanders will likely contain depositional point-bars that contain less substantial riparian vegetation, leaving the channel more exposed. Channels will be deeper due to the accumulation of upstream tributaries. Below the basalt gorge, where the Grande Ronde meets the Snake River, fluvial processes dominate in the lower-lying basin. Channel banks are not as constricted by canyon walls and are primarily composed of deposited sediments. In these lower reaches, channels are significantly wider and deeper and are able to transport a full range of sediment sizes.

In his work, Montgomery (1999) explains that the PDC is a “framework” though which disturbance regimes and environmental characteristics in river segments can be understood; and that it is not incompatible with or does not contradict the RCC. Rather, both the RCC and PDC can be used together to better understand the dynamic relationships between physical river characteristics and aquatic and riparian ecosystems. Montgomery (1999) goes on to say that in environments that have uniform climate, simple geology, and gentle topography that the RCC may prove to be a more applicable concept. Conversely, in an environment with variable climate, complex geology, and steep topography, like the Grande Ronde watershed, the PDC may be a more applicable concept (Fig. 12).

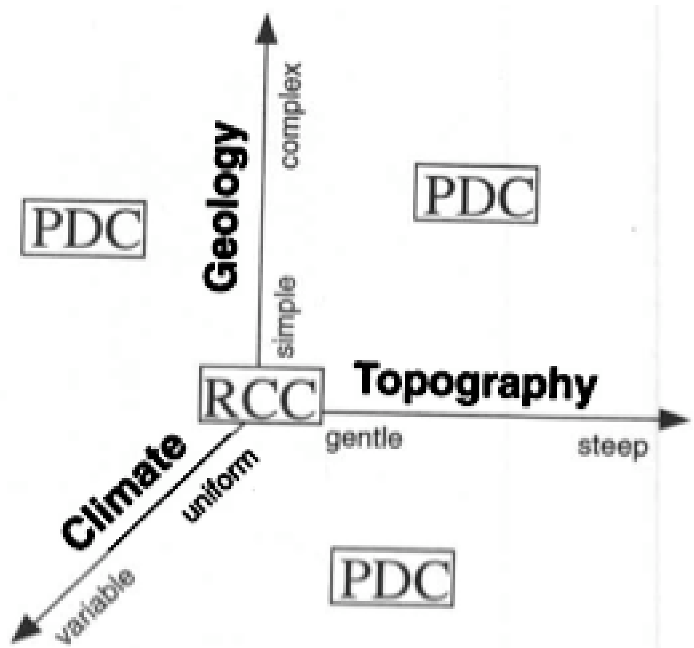

Figure 12. Hypothesized effects of climate, geology, and topography on the degree to which the geomorphic influences on aquatic ecosystems are described by the RCC and PDC. (Montgomery 1999)

CONCLUSIONS

The Grande Ronde River, and its associated tributaries, flows through a highly diverse and dynamic watershed in northeastern Oregon. This area has experienced significant geologic activity since the late Jurassic/early Cretaceous (160 – 100 Ma) when the large granitic Wallowa Pluton intruded, forming the present-day Wallowa Mountains. 17 Ma marked the initiation of eruption of the Columbia River Basalt Group, which would persist for the next 11.5 million years. The tectonic uplift that followed eruption of the flood basalts had equal influence in shaping the ancestral rivers that flowed across the region, and is responsible for much of the morphology we see today. Due to the complexity of physical factors in the Grande Ronde Watershed, it is difficult to fully characterize the river based on the River Continuum Concept (Vannote et al. 1980). Rather, the Process Domain Concept (Montgomery 1999) may provide a more applicable conceptual framework through which to view the physical and ecological interplay seen in the Grande Ronde River.

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