Reconciling detrital zircon and fish faunal evidence for Miocene-Pliocene drainage reorganization and basin integration of the Snake and Columbia Rivers

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Abstract

Miocene-Pliocene strata in the Pacific Northwest preserve a rich record of landscape evolution and coincident faunal shifts. Considerable research efforts in the past century have been aimed at understanding major drainage reorganization and its relation to tectonics, volcanism, climate change, and aquatic biota. Many studies have focused on fish fossils, which show that Miocene fish diversity, particularly salmonoids, displays great adaptive plasticity. However, the details and mechanisms for river reorganization are still debated. Here we present new and recent detrital zircon provenance results from modern and ancestral river sands collected throughout Oregon, Washington, and Idaho. We synthesize our new results and interpretations with existing paleontological evidence for basin isolation and drainage capture. Detrital zircons from the Columbia Basin (CB) consistently show populations derived from the Snake River Plain (SRP) throughout late Miocene-Pliocene time. However, comparisons of Miocene-Pliocene detrital zircons from the CB to modern major rivers and tributaries in the CB and SPR show that the upstream eastern SRP is a major contributor. CB strata do not require zircons sourced from the western SRP, where Pliocene Lake Idaho existed in a large, deep, and occasionally internally drained basin. Based on the age and provenance results, we suggest that the transiting Yellowstone Hotspot divided the modern SRP into two basins: the western basin was isolated and possibly closed, while the eastern basin drained northward into the modern Clark Fork and Columbia Rivers. This scenario is consistent with fish, mollusk, and rodent fossil evidence from the SRP and CB. In addition, the detrital zircon data indicate a Miocene confluence of the Columbia and Clearwater rivers south of the Saddle Mountains anticline, but north of the current Columbia-Snake River confluence. We also find that the Salmon River may have been captured by the Clearwater River sometime between 4.6 and 8.5 Ma. Prior to this time, the Salmon River likely drained into the SRP. Lastly, we find that faunal localities in southern Oregon suggested to contain evidence for fluvial connection between the western SRP and California are ~2.5 Ma, younger than the incision of Hells Canyon.

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ABSTRACT

Miocene-Pliocene strata in the Pacific Northwest preserve a rich record of landscape evolution and coincident faunal shifts. Considerable research efforts in the past century have been aimed at understanding major drainage reorganization and its relation to tectonics, volcanism, climate change, and aquatic biota. Many studies have focused on fish fossils, which show that Miocene fish diversity, particularly salmonoids, displays great adaptive plasticity. However, the details and mechanisms for river reorganization are still debated. Here we present new and recent detrital zircon provenance results from modern and ancestral river sands collected throughout Oregon, Washington, and Idaho. We synthesize our new results and interpretations with existing paleontological evidence for basin isolation and drainage capture.

Detrital zircons from the Columbia Basin (CB) consistently show populations derived from the Snake River Plain (SRP) throughout late Miocene-Pliocene time. However, comparisons of Miocene-Pliocene detrital zircons from the CB to modern major rivers and tributaries in the CB and SRP show that the upstream eastern SRP is a major contributor. CB strata do not require zircons sourced from the western SRP, where Pliocene Lake Idaho existed in a large, deep, and occasionally internally drained basin. Based on the age and provenance results, we suggest that the transiting Yellowstone Hotspot divided the modern SRP into two basins: the western basin was isolated and possibly closed, while the eastern basin drained northward into the modern Clark Fork and Columbia Rivers. This scenario is consistent with fish, mollusk, and rodent fossil evidence from the SRP and CB.

In addition, the detrital zircon data indicate a Miocene confluence of the Columbia and Clearwater rivers south of the Saddle Mountains anticline, but north of the current Columbia-Snake River confluence. We also find that the Salmon River may have been captured by the Clearwater River sometime between 4.6 and 8.5 Ma. Prior to this time, the Salmon River likely drained into the SRP. Lastly, we find that faunal localities in southern Oregon suggested to contain evidence for fluvial connection between the western SRP and California are ~2.5 Ma, younger than the incision of Hells Canyon.

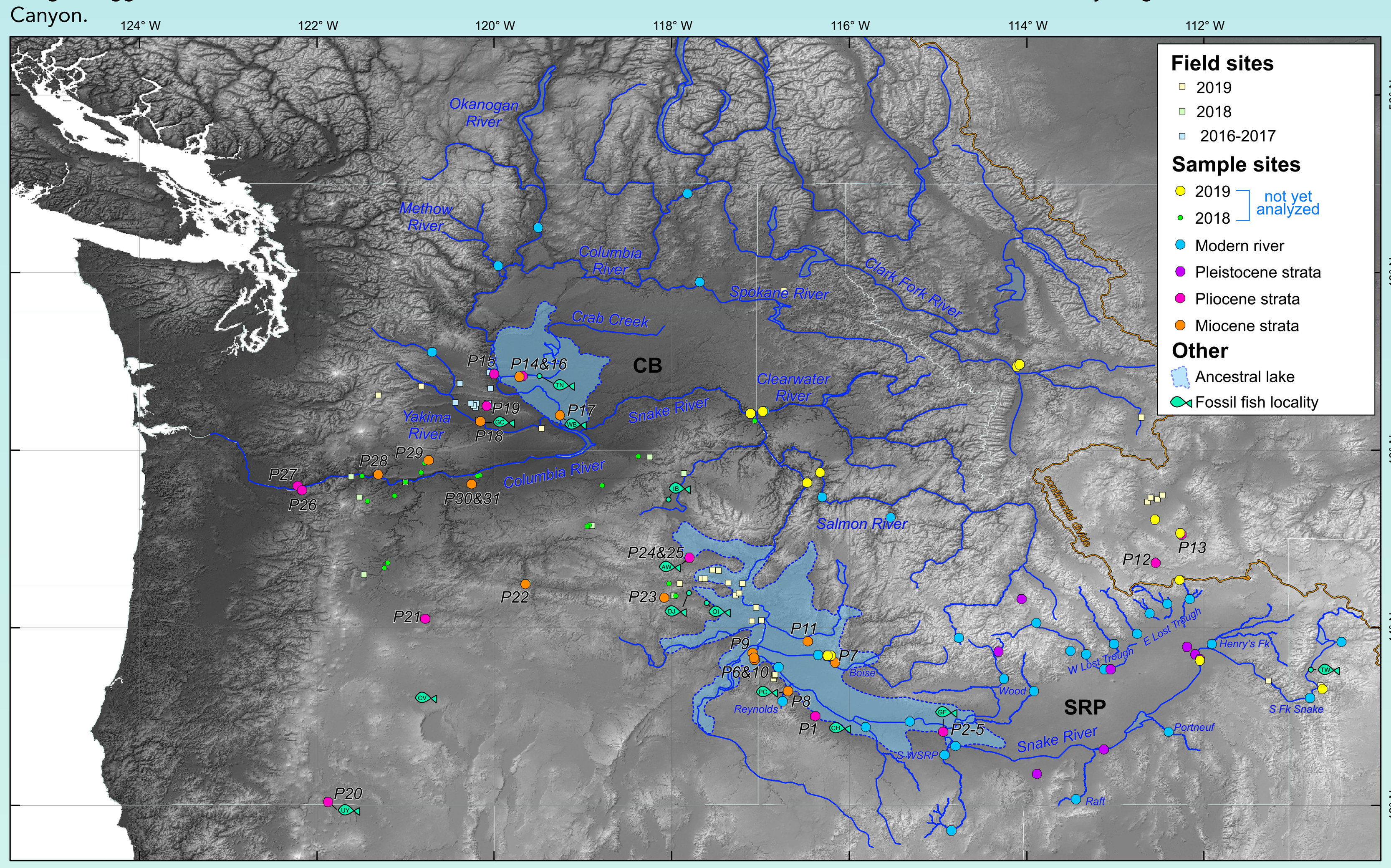

Figure 1. Topographic map of the Pacific Northwest and northern Rockies with site and sample locations for this study. Sampled fluvial strata are colored by their relative depositional age, except for unanalyzed samples with pending age results. The general location of paleo Lake Ringold and Lake Idaho are shown in a transparent blue overlay. Modern major fluvial systems are shown in dark blue. Site labels for ancestral river sandstone samples correspond to labels in Figures X-X and Tables X-X. Fossil fish localities correspond to Table X and are abbreviated as follows: TN = Taunton (Ringold), WB = White Bluffs (Ringold), GC = Granger Clay Pits, GF = Glenns Ferry Fm., CH = Chalk Hills Fm., PC = Poison Creek Fm., IB = Imbler, AW = Always Welcome Inn, DJ = Drewsey-Juntura, OI = Oregon-Idaho, UY = Upper Yonna Fm., CV = Christmas Valley, TW = Teewinot Fm.

GEOLOGIC SETTING AND MOTIVATION

Columbia Basin

The Ringold formation consists of fluvial and lacustrine strata in the Columbia Basin (CB). It preserves evidence for the Miocene-Pliocene (~10.3-3 Ma) Lake Ringold (Fig. 1)

Several productive fossil beds have been studied for fish and mammal paleontology along the White Bluffs and at the Taunton section north of the Saddle Mountains

Snake River Plain

The ~4.3 - 2.2 Ma Glenns Ferry and ~8.1 - 6.0 Ma Chalk Hills formations are lacustrine and fluvial strata deposited in the western Snake River Plain (SRP) and remnants of a once-massive Miocene-Pliocene lacustrine system (Fig. 1). A disconformity between the strata suggest that Lake Idaho had two separate phases

These and other similarly aged strata in the SRP and Oregon-Idaho graben area have produced fish and mammal fossil datasets comparable to those from the Ringold Fm.

The Debate

Considerable debate surrounds the when and how the Snake River Plain became connected to the Columbia Basin. Furthermore, the driving mechanisms of landscape evolution and basin integration remain enigmatic

The similarity of Taunton section Ringold and Glenns Ferry fossils were used to suggest basin integration <3 Ma via incision of Hells Canyon, however recent geochronologic data show that the Taunton fossils may be older (6.8 - 3.5 Ma; Staisch et al., 2017)

Prior to incision (and regardless of timing), there is little clarity on whether the SRP once drained into the Sacramento Valley via Oregon and/or Nevada (Wheeler & Cook, 1954; Repenning et al., 1995), that it was connected to the Columbia Basin across the Blue Mountains (Reidel & Tolan, 2013; Livingston, 1928), or had some other path

Table 1. Detrital zircon samples, ages, and source

Sample	*Age [Ma]*	*Source*
Snake River Plain		
P1 - Upper Glenns Ferry Fm.	2.2 - 3.3	Beraneck et al., 2006
P2 - Upper Glenns Ferry Fm.	2.2 - 3.3	Link et al., 2005
P3 - Lower Glenns Ferry Fm.	4.0 - 4.3	Link et al., 2005
P4 - Lower Glenns Ferry Fm.	4.0 - 4.3	Link et al., 2005
P5 - Tauna Gravel	2.2 - 3.3	Beraneck et al., 2006
P6 - Sucker Creek Fm.	15.5	Beraneck et al., 2006
P7 - Table Rock Fm.	10	Beraneck et al., 2006
P8 - Poison Ck. Fm.	8.1 - 11.0	Beraneck et al., 2006
P9 - Idaho Gr.	7	Beraneck et al., 2006
P10 - Idaho Gr.	7	Beraneck et al., 2006
P11 - Terteling Springs Fm.	6	Beraneck et al., 2006
Ruby Graben, SW Montana		
P12 - Sixmile Creek Fm.	< 5.1	Stroup et al., 2008
P13 - Sixmile Creek Fm.	< 5.5	Stroup et al., 2008
Eastern Washington		
Ringold Formation		
P14 - Smyrna Bench	3.48 ± 0.14	this study
P15 - Yakima Training Center	3.89 ± 0.58	this study
P16 - Smyrna Bench	6.83 ± 0.27	this study
P17 - White Bluffs	< 5.5	this study
Elsewhere in Columbia Basin		
P18 - Granger, WA	~7-10.5	this study
P19 - Black Rock Valley gravels	0.2 - 3.2	this study
Eastern Oregon		
P20 - Worden, OR salmon site	~ 2.5	this study
P21 - Deschutes fm.	3.2 - 4.0	this study
P22 - Rattlesnake Fm.	6.6	this study
P23 - Rattlesnake Fm. (?)	< 9.5	this study
P24 - Always Welcome Inn, lower	< 4.0	this study
P25 - Always Welcome Inn, upper	< 3.7	this study
Columbia River Gorge		
P26 - Troutdale Fm	< 3.0	this study
P27 - Columbia River gravels	3.0 - 4.57	this study
P28 - Miocene Klickitat gravels	9.93 ± 0.25	this study
P29 - Goldendale gravels	< 9.6	this study
P30 - Arlington Lake beds	~12.0	this study
P31 - Arlington Lake beds	< 14.5	this study

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METHODS

Detrital zircon LA-ICP-MS age dating

We collected modern sands from 7 major modern rivers and 18 Miocene-Pliocene fluvial sandstones in Washington, Oregon, and Idaho (Fig. 1; Table 1). New 2019 samples await analysis

For each sample, we dated ~120 zircons using U-Pb LA-ICP-MS (Laser Ablation Inductively Coupled Mass Spectrometry). Pit depths are typically <20 μm. The laser spot sizes for zircon were ~25 μm.

Ages were corrected by standard sample bracketing with the primary zircon reference material Temora2 (ca. 417 Ma; Black et al., 2004) and/or secondary reference materials FC-1 (ca. 1099 Ma, Paces & Miller, 1999), Plešovice (ca. 337 Ma, Sláma et al., 2008) and Fish Canyon tuff (ca. 28 Ma, Schmitz & Bowring, 2001)

$^{206}Pb/^{238}U$ ages are reported for igneous zircon samples less than ~1300 Ma and $^{207}Pb/^{206}Pb$ ages are used for older ages following the recommendations of Gehrels (2012)

Detrital zircon age spectra for measured modern rivers and a selection of Miocene - Pliocene sands are shown in Figure 2, below

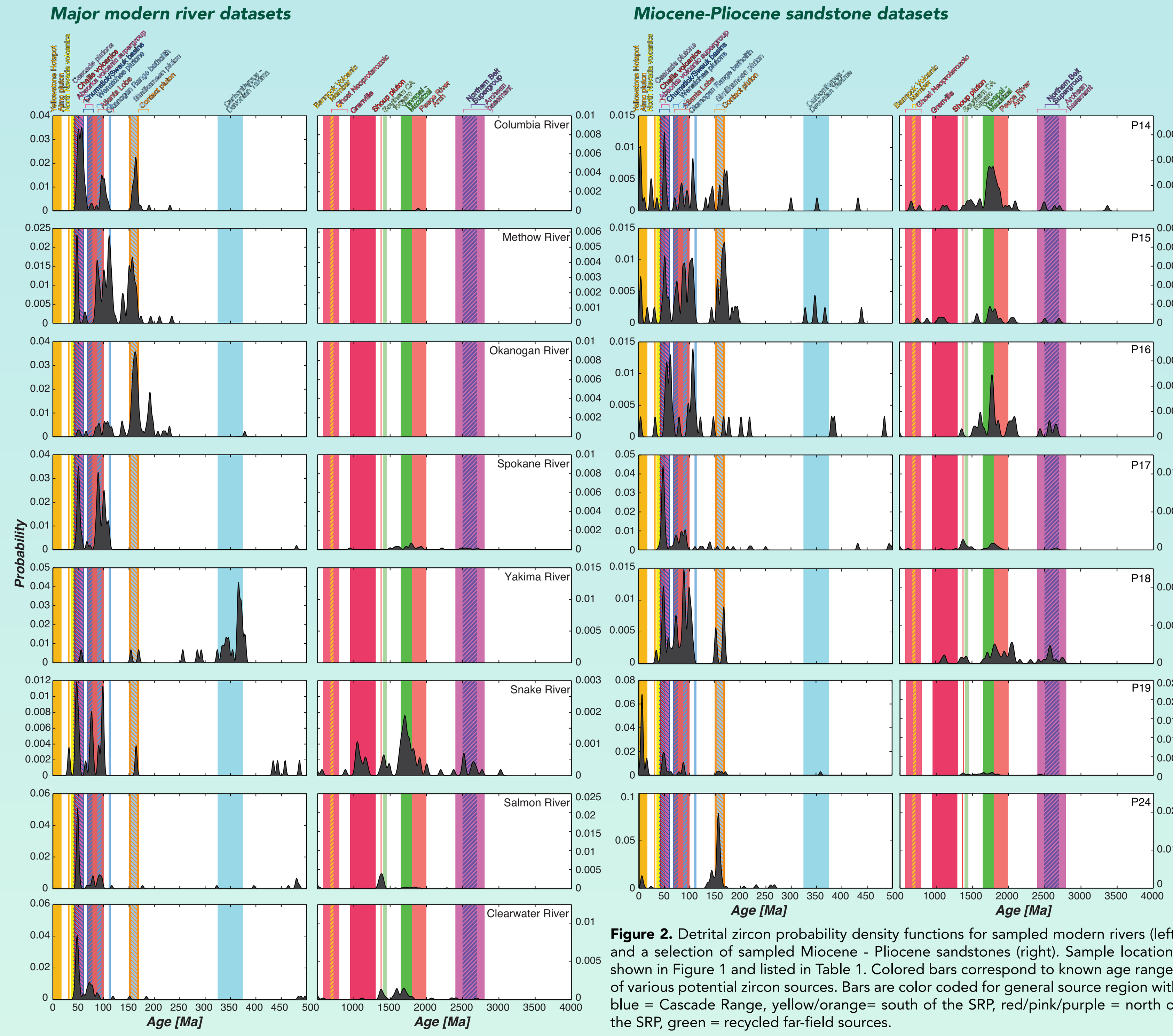

Figure 2. Detrital zircon probability density functions for sampled modern rivers (left) and a selection of sampled Miocene - Pliocene sandstones (right). Sample locations shown in Figure 1 and listed in Table 1. Colored bars correspond to known age ranges of various potential zircon source terranes. Bars are color coded for general source region with blue = Cascade Range, yellow/orange= south of the SRP, red/pink/purple = north of the SRP, green = recycled far-field sources.

Sample intercomparison - Multi-Dimensional Scaling

For sample intercomparison, we employ Multi-Dimensional Scaling (MDS), a technique that is becoming increasingly used on large detrital zircon datasets

MDS essentially constructs plots based on sample similarity, in which samples that cluster together are more similar, whereas samples that are spread out are less similar (Vermeesch, 2013). To construct MDS plots, we use the software available from Saylor et al. (2017)

We compare new and existing detrital zircon datasets from sandstone samples collected from the Columbia Basin, Snake River Plain with each other and with modern river samples to discern similarities between strata and potential source terranes (Fig. 4)

For the available metrics, we found that the most consistent results and lowest stress values were achieved by using PDP Likeness, Kuiper V, and K-S D metrics of similarity

Detrital zircon spectra unmixing

Sandstones sampled from ancestral river networks may be downstream of major confluences, especially in the CB. To determine the relative contribution of major river networks to a single sample, we used the DZMix software from Sundell & Saylor (2017)

Modern river detrital zircon datasets were used as potential sources for Miocene-Pliocene samples (Figs. 2 & 3A). We acknowledge the likelihood that modern river networks are not entirely equivalent to those in the past, however the benefit of modern rivers is that we known their upstream drainage area

We tested three hypothetical river network combinations:
(1) All major modern rivers (Snake model)
(2) Modern rivers, except the Snake River (No Snake model)
(3) No Snake model but with tributaries in the east Snake River Plain (Only ESRP model).

For each model of each sample, we ran 100,000 trails and retained the top 1% (Fig. 3B). We recorded the goodness of fit between modeled and measured detrital zircon datasets. Goodness of fit (GOF) was assessed using three statistical metrics: Kuiper V-statistic, K-S D-statistic, and cross correlation. Values range between 0 and 1, 1 being a perfect fit

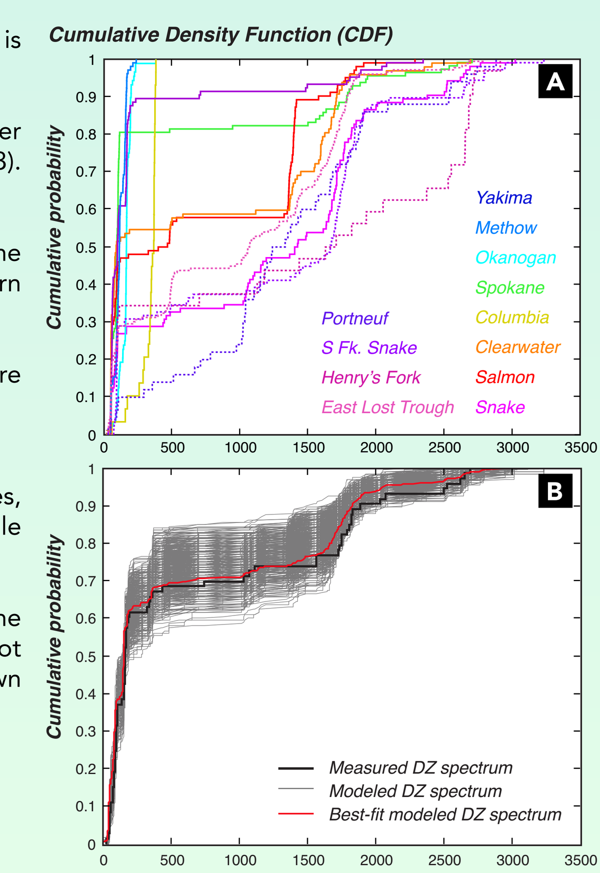

Figure 3. (A) CDF of modern river detrital zircon data sets used in various DZmix modeling experiments. (B) Example CDF of a model run showing the measured DZ spectrum (black), top 1% of modeled spectra (grey) and best-fit modeled spectrum (red).

RESULTS AND INTERPRETATION

Sample intercomparison - Multi-Dimensional Scaling

- Miocene-Pliocene Lake Ringold strata cluster more closely to modern rivers that source the northern Rockies than Cascadian rivers (Fig. 4)
- Sixmile Creek Fm. is more similar to Ringold than Glenns Ferry Fms. It also clusters more closely with tributaries in the ESRP (Fig. 4)
- Miocene-Pliocene samples from the Columbia River Gorge fall between upstream Lake Ringold and Lake Idaho samples (Fig. 4)
- Samples from eastern Oregon plot away from coeval sediments from the SRP and the CB (Fig. 4)

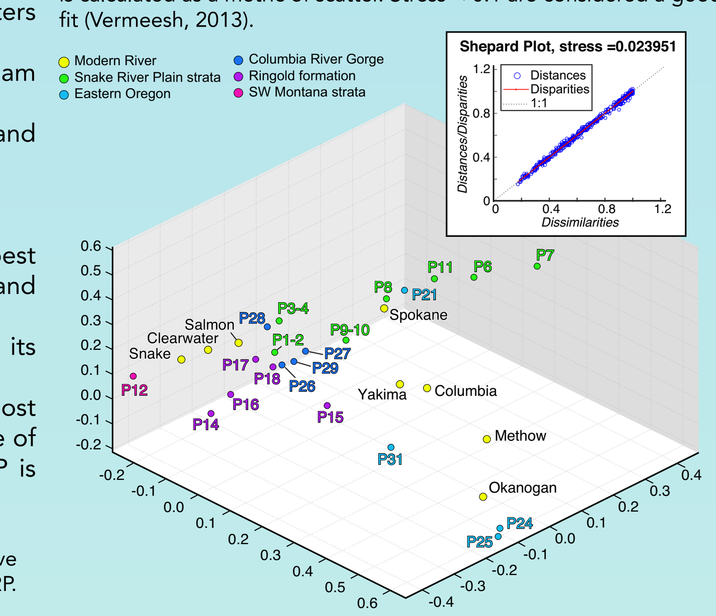

Figure 4. Example MDS plots using the PDP Kuiper V-statistic. For each plot, a sample dissimilarity matrix and sample coordinates for 3D MDS plots are calculated. Shepard plots assess model fit, where stress is calculated as a metric of scatter. Stress < 0.1 are considered a good fit (Vermeesh, 2013).

Detrital zircon spectra unmixing

- Goodness of fit generally suggests that the "Only ESRP" model provides the best fit to measured detrital zircon datasets throughout the Columbia Basin and Columbia River Gorge (Table 2)
- The Snake River is an important contributor to Lake Ringold throughout its depositional history (Fig. 5)
- Miocene-Pliocene samples collected at and downstream of the White Bluffs, most of which were likely are south of Lake Ringold, show an increased importance of the Clearwater and Salmon Rivers as major contributors, whereas the ESRP is more important upstream of the White Bluffs (Fig. 5)

Figure 5. DZMix results for the "Only ESRP" model. Pie charts show the modeled relative proportion of modern rivers contributing to Miocene-Pliocene sandstones from the CB and SRP. Percentages are a for the best-fit results based on Kuiper V, K-S D, and cross correlation statistics.

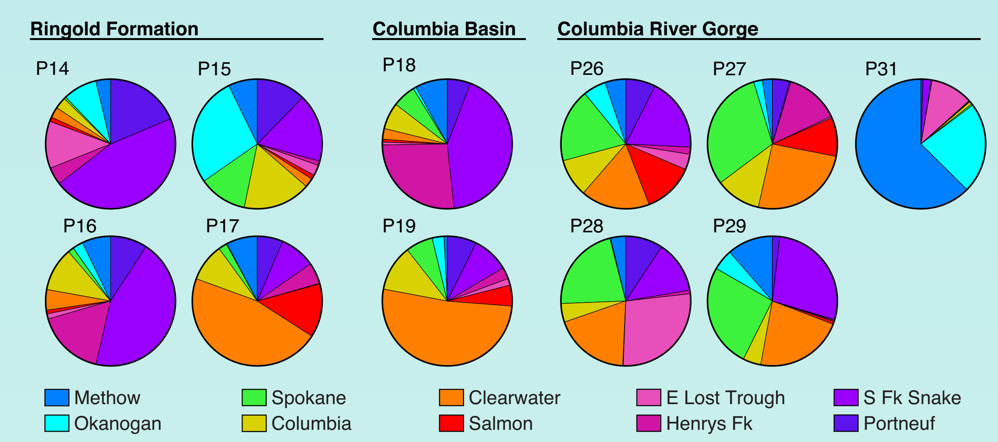

Table 2. Mean goodness of fit values for DZ Mix models. Values range from 0 - 1, 1 being a perfect fit. Best values highlighted in teal.

	Mean Goodness of Fit		
	All Snake	*Only ESRP*	*No Snake*
Ringold Formation			
P14 - Smyrna Bench (upper)	0.801	**0.828**	0.642
P15 - Yakima Training Center	**0.954**	0.934	0.902
P16 - Smyrna Bench (lower)	0.805	**0.834**	0.704
P17 - White Bluffs (Taylor Flat conglom)	0.917	**0.922**	0.912
Columbia Basin			
P19 - Black Rock Valley gravels	**0.928**	0.927	0.918
P18 - Snipes Mtn. conglom	0.839	**0.882**	0.766
Columbia River Gorge			
P26 - Troutdale formation	**0.951**	**0.951**	0.927
P27 - Columbia River gravels	0.916	**0.930**	0.913
P28 - Klickitat gravels	0.861	**0.866**	0.843
P29 - Goldendale gravels	0.932	**0.937**	0.905
P31 - Arlington lake beds	**0.788**	**0.788**	0.787

Paleontological data

- The Glenns Ferry lake fauna include *Oncorhynchus tshawytscha*, a rare anadromous salmon (Sterling & Smith, 2016)
  Evidence for connection to the Pacific Ocean at some point between 4.3 and 2.2 Ma
  Occurrence of salmonoids in Lake Idaho requires that it was large, deep, oxygenated to the bottom, and fed by high altitude streams
- While early-mid Miocene basins in NE Oregon (Oregon-Idaho & Drewsey-Juntura grabens) show prior connection between the CB and SRP, unique Pliocene fish fauna in Baker and Grande Ronde Valleys suggest at least 1 Ma of isolation (Table 3; Van Tassell & Smith, 2019)
  No strong evidence for Pliocene alternate route across the Blue Mountains, but perhaps an earlier (<~6 Ma) filtered headwater connection
- Discordant *Chasmistes muriei* fossils from the <7.45 Ma Teewinot formation (in Wyoming) are most similar to lake sucker fossils from Glenns Ferry and Chalk Hills Lakes (Miller and Smith, 1981)
  Potential connection between Miocene and Pliocene WSRP lakes and upper Snake River drainage

Table 3. Fish fossil Genus identified from paleontological localities. Table modified from Van Tassell & Smith (2019).

	Fossil Localities	*Basin/Valley*	*Age [Ma]*	Acipenser (Sturgeon)	Ameiurus (Catfish)	Orthodon (Blackfish)	Ptychocheilus (Pikeminnow)	Mylopharodon (Hardhead)	Siphateles (Tui Chub)	Lavinia (Hitch)	Gila / Klamathella (Chub)	Klamathella (Chub)	Acrocheilus (Chiselmouth)	Mystocheilus (Chub)	Richardsonius (Shiner)	Mylocheilus (Peamouth)	Rhinichthys (Dace)	Oregonichthys (Oregon Chub)	Deltistes (Lost R Suckers)	Chasmistes (Lake Suckers)	Catostomus (River Suckers)	Pantosteus (Mtn. Suckers)	Prosopium (Whitefish)	Paleolox/Salvelinus (Char)	Oncorhynchus trout (Trout)	Oncorhynchus salmon (Salmon)	Esox (Muskellunge)	Plioplarchus/Mioplites (Large Sunfish)	Archoplites (Small Sunfish)	Cottus (River Sculpin)	Myoxocephalus (Sculpins)	Kerocottus (Lake Sculpins)
CB	Ringold Fm. - north	Pasco Basin	6.8 - 3.4	●	●		●			●		●	●			●				●	●						●		●			
CB	Ringold Fm. - south	Pasco Basin	10.3 - 4.2	●	●		●									●				●	●					●	●		●			
CB	Granger clay pits	Yakima/Pasco	10.5 - 7.0 (?)		●		●	●		●		●										●							●			
SRP	Glenns Ferry Fm.	Snake River Plain	4.3 - 2.2		●	●	●	●		●		●	●		●	●	●		●	●	●	●	●		●	●			●	●	●	●
SRP	Chalk Hills Fm.	Snake River Plain	8.1 - 6.0		●	●	●	●		●			●			●			●	●	●			●	●	●			●	●		
SRP	Poison Creek Fm.	Snake River Plain	11.0 - 8.1		●	●	●	●					●			●					●			●					●			
OR	Imbler	Grande Ronde Valley	3.6 - 3.5		●	●																	●						●			
OR	Always Welcome Inn	Baker Valley	4.5 - 3.7				●						●	●			●				●	●		●					●	●		
OR	Drewsey-Juntura Graben	Malheur River	13.6 - 7.25		●	●	●	●		●	●		●	●		●		●	●	●	●	●		●			●		●			
OR	Oregon-Idaho Graben	Owyhee River	15.9 - 12.8		●		●			●														●			●	●	●			
CA	Upper Yonna Fm.	Klamath River Valley	4.5 - 2.5													●					●				●							
CA	Upper Alturas	Sacramento River	4.8 - 4.5				●		●	●		●								●	●					●				●		
CA	Christmas Valley	Fort Rock Basin	5.0 - 4.9						●											●	●					●						

No. of species: ● 1, 2, 3, 4, 5

Based on detrital zircon age spectra, MDS comparisons, and DZMix modeling, we suggest that the Snake River has been a continuously present contributor of sediment into the Columbia Basin since the late Miocene onset of lacustrine Ringold formation deposition, ca. ≥6.8 Ma

The dissimilarity of detrital zircon spectra and fossil evidence for isolation of eastern Oregon intermontane basins indicates that the Blue Mountains were not a likely pre-Hell Canyon route for the Snake River, disproving routes proposed by Livingston (1928) and Reidel & Tolan (2013)

Our data do not support a Miocene connection of the Snake River and Sacramento river prior to incision of Hells Canyon, however we cannot discount the possibility that the east and west SRP were temporarily disconnected and that Lake Idaho drained into the Sacramento drainage

The similarity in detrital zircon spectra of the Sixmile Creek and Ringold Fms., along with improved DZMix modeled fit of the "Only ESRP" model suggests that the Miocene-Pliocene Snake River may have circumnavigated the western SRP. Our prefered model is that the Snake entered the CB via the Clark Fork River (Fig. 6)

Samples collected downstream of the White Bluffs show an increased importance of the Salmon and Clearwater river components, suggesting confluence at or near the White Bluffs. Importantly, this supports our inference that the modern confluence of the Snake and Salmon rivers postdates the Ringold Fm. (<3 Ma)

Fish faunal evidence still suggests that the Ringold and Glenns Ferry formations shared a through-going fluvial route, which we suggest was potentially through the eastern SRP or via the Salmon River (Fig. 6)

The 6-4 Ma location of the Yellowstone Hotspot at the Heiss Volcanic Center in the ESRP and its transient effect on dynamic topography in the region provides a potential mechanism for our proposed ancestral route for the Snake River (Fig. 6)

Furthermore, Miocene uplift of the Blue Mountains and coincident tectonic subsidence of the western SRP may have contributed to the formation and long-lived existence of Lake Idaho (Fig. 6)

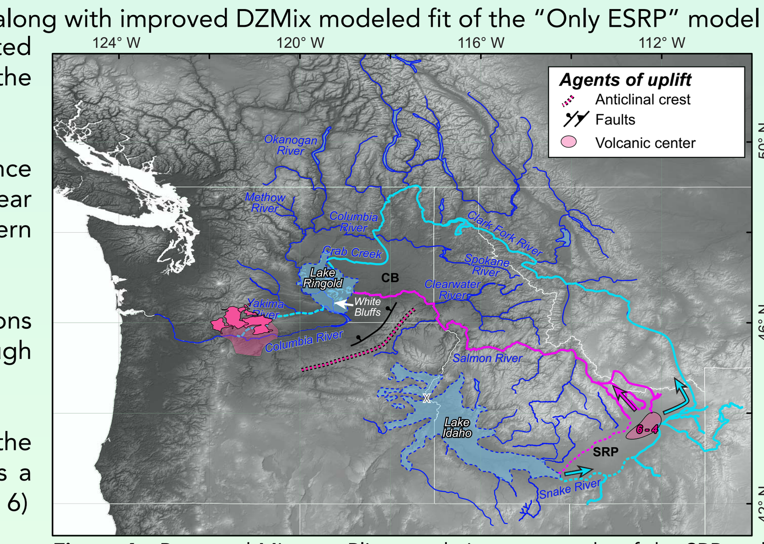

Figure 6. Proposed Miocene-Pliocene drainage networks of the SRP and CB, based on detrital zircon and fish faunal datasets. Coeval volcanic centers, including the Simcoe volcanics and Heiss Volcanic center, and the potentially Blue Mountains anticline, shown for reference.