

## AN ABSTRACT OF THE THESIS OF

Kiya L. Wilson for the degree of Honors Baccalaureate of Science in Earth Science presented on May 24, 2011. Title: Using An Array of NE Pacific Margin Sediment Samples to Link Land and Ocean Responses to Glacial-Interglacial Climate Variability.

Abstract approved: \_\_\_\_\_

Robert A. Duncan

Variability in the terrigenous (land-derived) fraction of marine sediments, including pollen and rock fragments, reflects the effects of regional climate change on continentally derived runoff, ice extent, vegetation and ocean circulation. The transport of this continental material to the seafloor must be understood in order to interpret the terrigenous sediment record. This is investigated using several geochemical tracers to identify transport pathways of material from Pacific Northwest rivers to continental margin depositional sites.

We report the results of  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating and  $\epsilon_{\text{Nd}}$  of bulk detrital sediments (20-63 $\mu$  fraction) from core tops in an array of thirteen sites along the continental margin of the Pacific Northwest. Geochemical signatures of sediment transport along the continental margin are found to reflect proximal river sources reported by VanLaningham et al. (2006), and the seasonal effect of northward flow in the Davidson Current. This study provides the 'proof of concept' needed to describe down-core changes in detrital sediment source and accumulation rate over the last 30ka at 3 sites within this array. Comparison of such changes to highly correlated variability in pollen and plankton assemblages will distinguish terrestrial landscape changes from

changes in ocean circulation, as Pacific NW climate changed from glacial to present conditions.

**Key Words:** marine sediments, provenance, neodymium isotopes, argon dating, climate variability

Corresponding email address: [kiya.l.wilson@gmail.com](mailto:kiya.l.wilson@gmail.com)

©Kiya L. Wilson  
May 24, 2011  
All Rights Reserved

Using An Array of NE Pacific Margin Sediment Samples to Link Land and Ocean  
Responses to Glacial-Interglacial Climate Variability

by

Kiya L. Wilson

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of  
the requirements for the  
degree of

Honors Baccalaureate of Science in Earth Science (Honors Scholar)

Presented May 24, 2011  
Commencement June 2011



Honors Baccalaureate of Science in Earth Science project of Kiya L. Wilson presented on May 24, 2011.

APPROVED:

---

Mentor, representing College of Oceanic and Atmospheric Sciences

---

Committee member, representing College of Oceanic and Atmospheric Sciences

---

Committee member, representing College of Oceanic and Atmospheric Sciences

---

Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

---

Kiya L. Wilson, Author

## ACKNOWLEDGEMENTS

In 2008, I knocked on Bob Duncan's door, an undergraduate lacking direction in my studies and with effectively no lab experience under my belt. Three years later I know that I want to get my PhD and enter the world of academia as a professor myself, in large part because of my experience with this project. Bob and Nick Pias together have introduced me to the world of academia. They have taught me how to write grants, present at conferences, use a mass spectrometer, spell the word 'material' correctly.... and have fun while doing it. I cannot thank them both enough for taking me under their wings these last few years. I have loved every minute of it.

This project is based on the continuation of Sam VanLaningham's thesis work. Sam- thank you thank you, for handing me your data and teaching me the ropes with such style.

David Graham, Andy Ungerer, Frank Tepley, Mee-Ya Monnin, Maya Heck and Mysti Weber were instrumental in helping me with lab work. Thank you all for welcoming me into your labs. I'm sorry for being the occasional klutz who breaks expensive things (particularly sorry about that one centrifuge!). Thank you also to my committee member Anthony Koppers, for the editing support and oceanography education over the years.

Thank you to NSF's REU program, the University Research, Innovation, Scholarship, and Creativity fund, the Geosciences Department of OSU, the University Honors College, and OSU's College of Oceanic and Atmospheric Sciences for many years of funding support.

Finally, to my rocks: Ma, Pa, Tan, and RJ. Thanks for being my support through the good and the bad. I love you guys.

## TABLE OF CONTENTS

BACKGROUND .....	1
Background on Methods Used.....	12
Site Description.....	16
METHODS .....	20
RESULTS .....	23
TT063-19PC and the Fraser River .....	28
TT063-13AC .....	30
TT063-10PC .....	30
W7905A-114TW .....	33
MV9907-20TC.....	33
Y6509-004PC .....	36
W7905A-134PC.....	36
Y6705-22PC .....	39
Y7211-1GC.....	39
Y6604-11PC .....	42
Y6604-12PC .....	42
Y74-1-08MG.....	45
Y-73-10-100MG .....	46
DISCUSSION.....	48
IMPLICATIONS AND FUTURE WORK.....	52
BIBLIOGRAPHY .....	54

## LIST OF FIGURES AND TABLES

<u>Figure</u>	<u>Page</u>
1. Core Site EW9504-17PC, northeast Pacific Ocean, pollen and radiolaria concentrations .....	4
2. Location of 14 Pacific Northwest rivers ‘fingerprinted’ by VanLaningham et al. (2006) .....	6
3. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of bulk sediments discharged by Pacific Northwest rivers .....	7
4. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of Pacific Northwest rivers .....	8
5. Typical $^{40}\text{Ar}$ - $^{39}\text{Ar}$ age spectra .....	13
6. Location of 14 marine sediment cores analyzed .....	21
7. $^{40}\text{Ar}/^{39}\text{Ar}$ results from marine sediment core tops .....	25
8. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core TT063-19PC .....	29
9. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core TT063-13AC .....	31
10. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core TT063-10PC .....	32
11. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core W7905A-114TW .....	34
12. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core MV9907-20TC .....	35
13. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y6509-004PC .....	37
14. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of sediment core W7905A-114TW .....	38
15. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y6705-22PC .....	40
16. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y72-11-1GC .....	41
17. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y6604-11PC .....	43
18. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y6604-12PC .....	44
19. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y74-1-08MG .....	46

20. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age and $\epsilon_{\text{Nd}}$ of sediment core Y73-10-100MG .....	47
21. Hypothesized sediment transport from PNW rivers to sample locations .....	49

<u>Table</u>	<u>Page</u>
1. Rivers of the Pacific Northwest .....	17
2. % <i>C. borealis</i> found in core tops .....	24
3. Summary of core locations and results .....	27

# Using An Array of NE Pacific Margin Sediment Samples to Link Land and Ocean Responses to Glacial-Interglacial Climate Variability

## **BACKGROUND**

Marine sediments are particles of mud, rock, and organic matter that continuously accumulate at the bottom of the ocean as new particles are deposited on top of older layers. The kinds of particles settling on the seafloor depend on many factors, like proximity to land, nearby rivers or glaciers, the amount of dust in the atmosphere, and the composition and production rate of organisms in the water column (Segar, 2007). As the Earth changes through time, buried sediments record what is happening in the ocean, on land, and in the atmosphere. Ocean sediments contain records of erosion of the continents, evolution of life, ocean environmental conditions and climate change history. By extracting long cores of these sediments, oceanographers are able to study Earth's climate history. Marine sediments can be more than a kilometer thick in certain places around the globe, and up to 170 million years old (Segar, 2007). Paleoclimatology, or the study of past climates, will be vital in the continued process of developing regional and global climate models capable of accurately predicting future climate change. This thesis examines the use of marine sediments in studying the connections between land and ocean climate, over time scales of 100s to 10,000s of years.

There are two main classes of marine sediments: those that originated on land, and those that originated in the ocean. These two classes are mixed in the water column, and settle to the sea floor. This study will focus on biologic material produced in the

ocean water column, and particles of soil, rock and organic matter that have been transported from land to the ocean.

Plankton live, grow, and die within the water column of the ocean. Once they die, their skeletal parts sink to the seafloor and are sometimes preserved in marine sediments. Radiolaria are a variety of zooplankton that form intricate shells made of silica. Certain species of radiolaria prefer warm tropical climates, while others prefer cold arctic waters. By identifying radiolaria species found in a sediment record at a given site, researchers can determine the approximate surface temperature of the water at the time that they were deposited.

Rivers scour material from the bedrock over which they flow and transport some of those particles into the ocean. Pollen from vegetation is transported by wind and water into rivers and then may reach the sea. These rocks and pollen slowly settle to the seafloor and mix with ocean-originating sediments. Different river systems transport a 'signature' combination of sediment types into the ocean. For example, the rivers in Hawaii transport much younger sediments into the ocean than rivers in the Pacific Northwest, because the bedrock of Hawaii was recently formed. When a given river's 'signature' sediment is known, sediment found on the seafloor can be traced to its on-land origin in a process known as a provenance study. There are many factors that influence the type and amount of sediment transported by rivers into the ocean. Rainfall, temperature, the character of the bedrock, and the presence of vegetation are all direct controls on the amount of material transported by rivers from land to the ocean. As a region's climate changes, the sediment discharged by its rivers changes as well. On an annual cycle, more material may be washed out to the ocean during the winter and spring



when storms are stronger and there is more precipitation (Sverdrup et al., 2003). Once rivers discharge material into the ocean, ocean currents dictate where they settle (Pisias et al., 2006). As climate changes over the ocean, ocean currents change, and the pattern of deposition of land-originating material also changes. In this way, terrigenous (land-originating) sediments found on the seafloor provide a record of changes in the land/ocean climate system.

Studies have found that the marine and terrigenous components of sediments show synchronous change, indicating that the land and ocean responses to climate change are tightly coupled. Pisias et al (2001) found that Pacific Northwest continental margin marine sediments of the last 15,000 years contain redwood tree pollen and cold-water loving radiolaria that appear simultaneously in the sediment record (see Figure 1). Northern California experiences primarily northerly winds in the summertime, which cause warm surface waters to be transported offshore and cold bottom waters to be brought to the surface near the coastline. Cold-water loving radiolaria flourish, and the upwelling of cold water produces coastal fog. Redwood trees along the coastline thrive when there is heavy coastal fog. Pisias et al. (2001) found that redwood pollen concentration in the marine sediments vary synchronously with cold-water loving radiolaria concentration. When redwood pollen is abundant, so are cold-water loving radiolaria. This provides strong evidence that changes in climate in the Pacific Northwest occur simultaneously over both land and ocean.

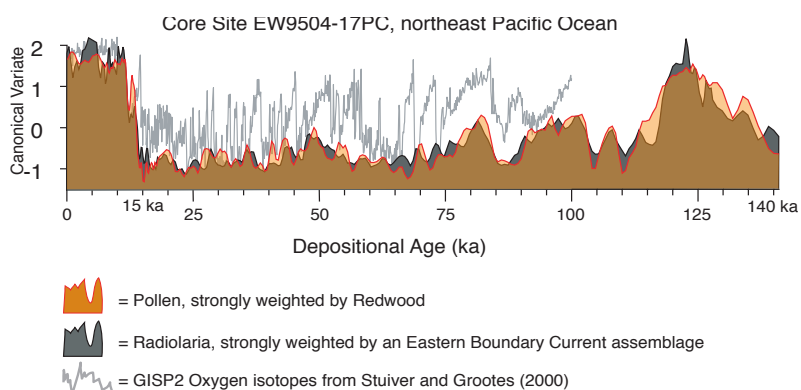


Figure 1: Core from the northern California margin shows correlation between redwood pollen and an assemblage of radiolaria indicative of an eastern boundary current: the California Current (VanLaningham, 2007).

The question remains, however, whether the apparent coupling of the terrestrial-ocean climate systems observed in the marine sediment record is due to serendipitous pollen transport change or true coupling of the systems. Do changes in the pollen record signify changes in vegetation on land, or changes in ocean currents resulting in the pollen being deposited elsewhere? Do changes in the sediments found at a given site reflect a change in erosion, ice extent, runoff and precipitation on land, or a change in ocean currents and deposition? This study will address these questions by examining the fidelity by which Pacific Northwest margin sediment sites record the terrigenous sediment input of proximal rivers on glacial-interglacial timescales.

In order to dig into these questions it is necessary to develop a record of the transport of material from land to the ocean over glacial/interglacial cycles at an array of sampling sites. VanLaningham et al. (2008) performed a similar study for a single core located just off the continental margin of southern Oregon. The provenance methods

developed in that study will be used here: a combination of Nd isotope analysis and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of bulk sediments. This kind of provenance work is possible because of prior work done by VanLaningham et al. (2007) in examining the sediments discharged by Pacific Northwest rivers into the NE Pacific ocean (see Figure 2 for location of rivers). VanLaningham et al.'s (2007) results are summarized in Figures 3 and 4. If the unique sediment composition of a river's discharge is known, it is possible to identify the river sources of sediments found offshore. Because VanLaningham et al. (2007) have collected and analyzed samples from the fourteen major rivers in this region's study area, it is possible for this study to identify the river-source of sediment found off the shelf.

The first step in conducting a large-scale provenance record for the NE Pacific is to look at modern sediments (i.e., sediments that have been deposited since the last glacial maximum about 22,000 years ago). After establishing modern distribution of sediments, it will be possible to look deeper into three selected cores within the array to see how sediment transport and distribution was different in the past. The scope of this study is to describe modern sediment transport to provide a baseline for future studies that look deeper into the same cores and develop this provenance record.

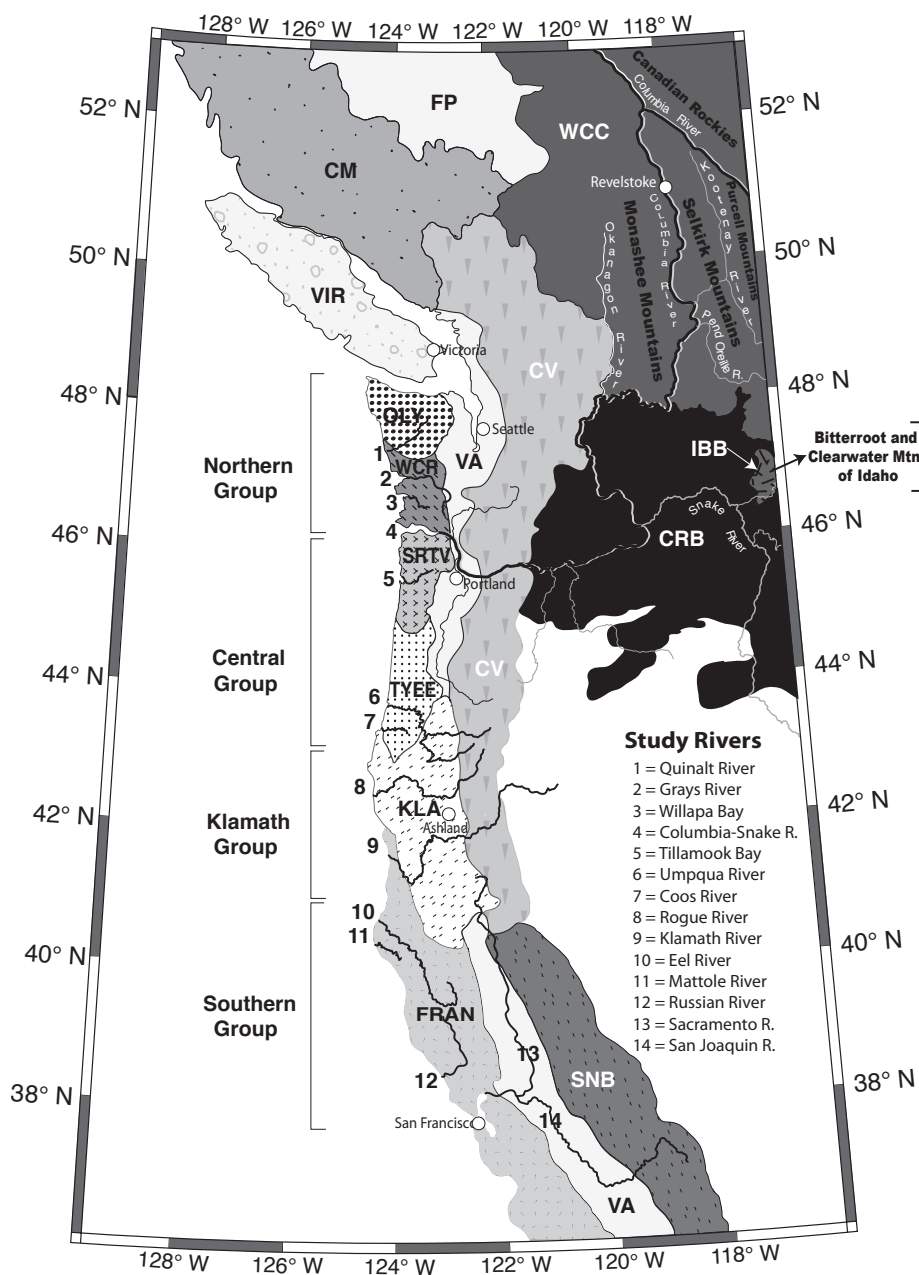


Figure 2: Location of 14 rivers for which bulk river mouth sediments have been ‘fingerprinted’ by combining Ar-dating and  $\epsilon$ Nd tracers, and the source terrains contributing to those geochemical signatures. (VanLaningham et al. 2006).

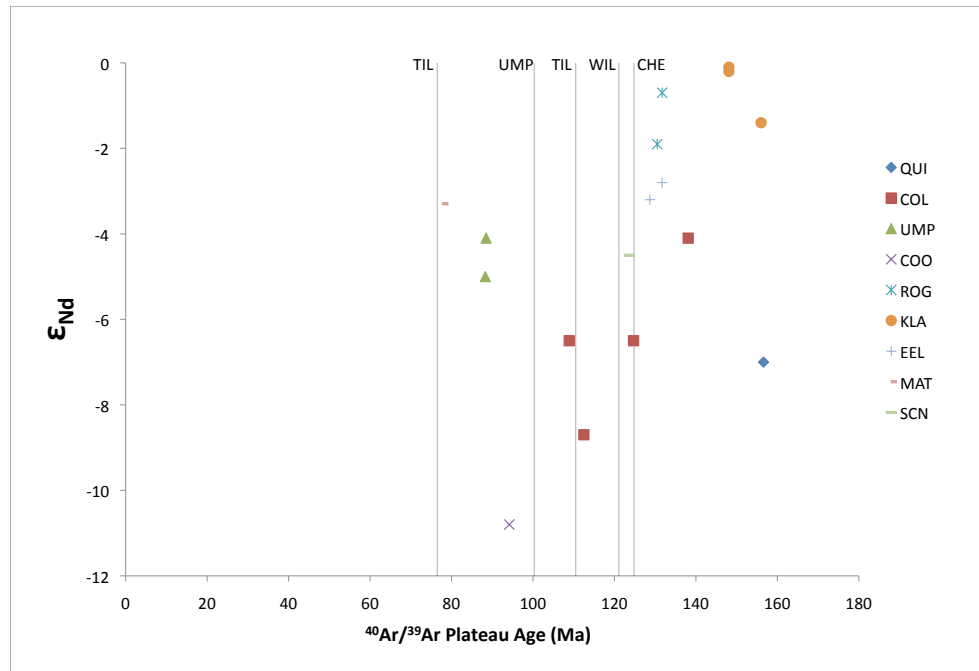


Figure 3:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age and  $\epsilon_{\text{Nd}}$  of bulk sediments (20-63  $\mu\text{m}$  size fraction) discharged by Pacific Northwest rivers. Vertical lines represent river sediments whose Ar age was determined but whose  $\epsilon_{\text{Nd}}$  was not measured. Error bars are  $\pm 2\sigma$ . In subsequent figures, error bars will not be included (note that most error bars do not extend beyond the symbol). Data source: VanLaningham, 2007.

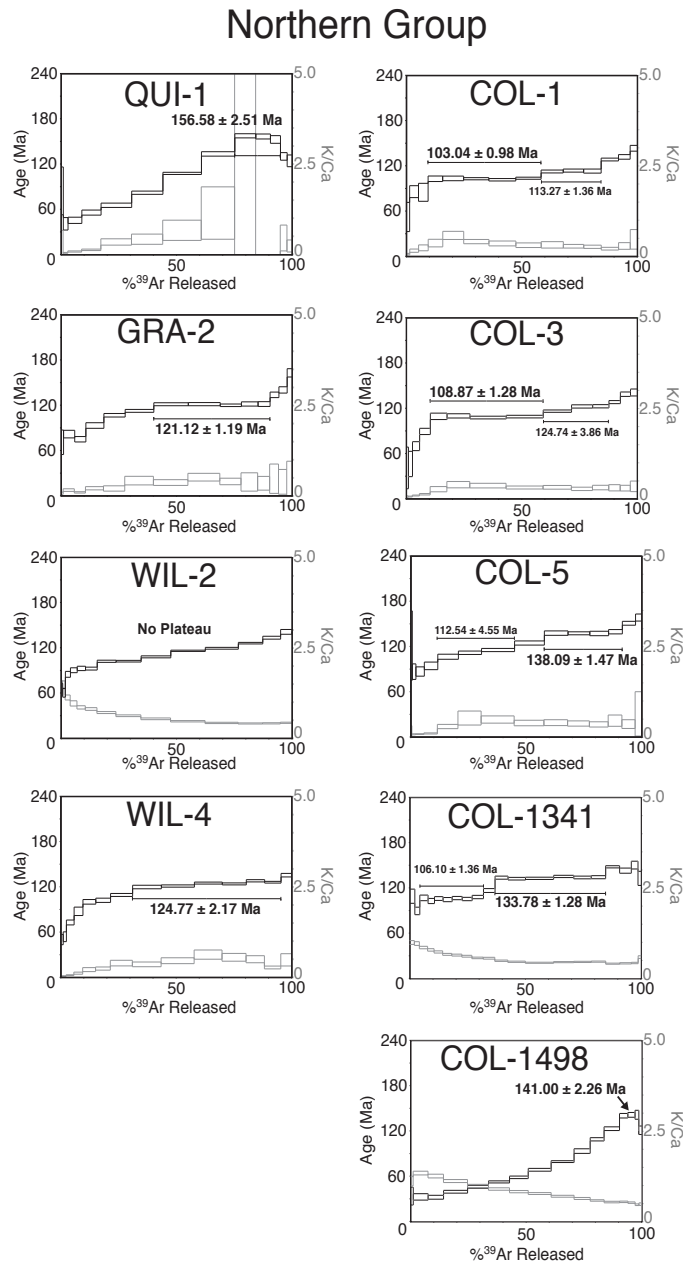


Figure 4:  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating spectra and K/Ca spectra for Pacific Northwest river sediments (VanLaningham et al. 2006). Analytical uncertainties (2-sigma) related to age and K/Ca are depicted by vertical scaling of each step-heating box. See Figure 5 for further explanation of  $^{40}\text{Ar}/^{39}\text{Ar}$  plots.

## Central Group

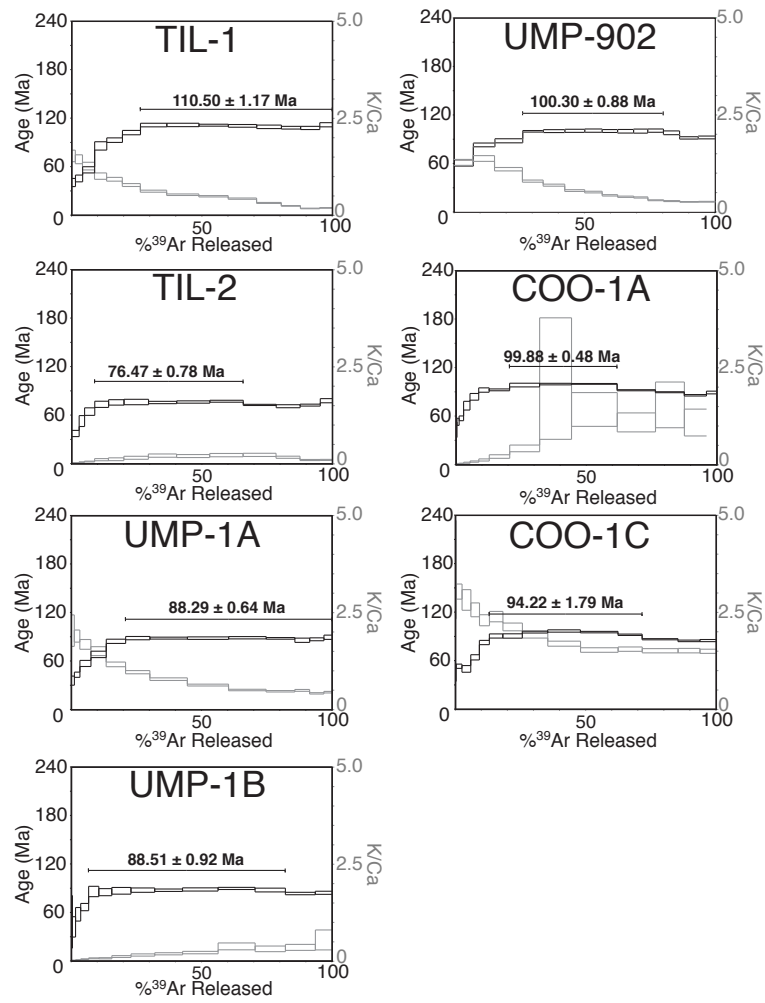


Figure 4 continued

## Klamath Group

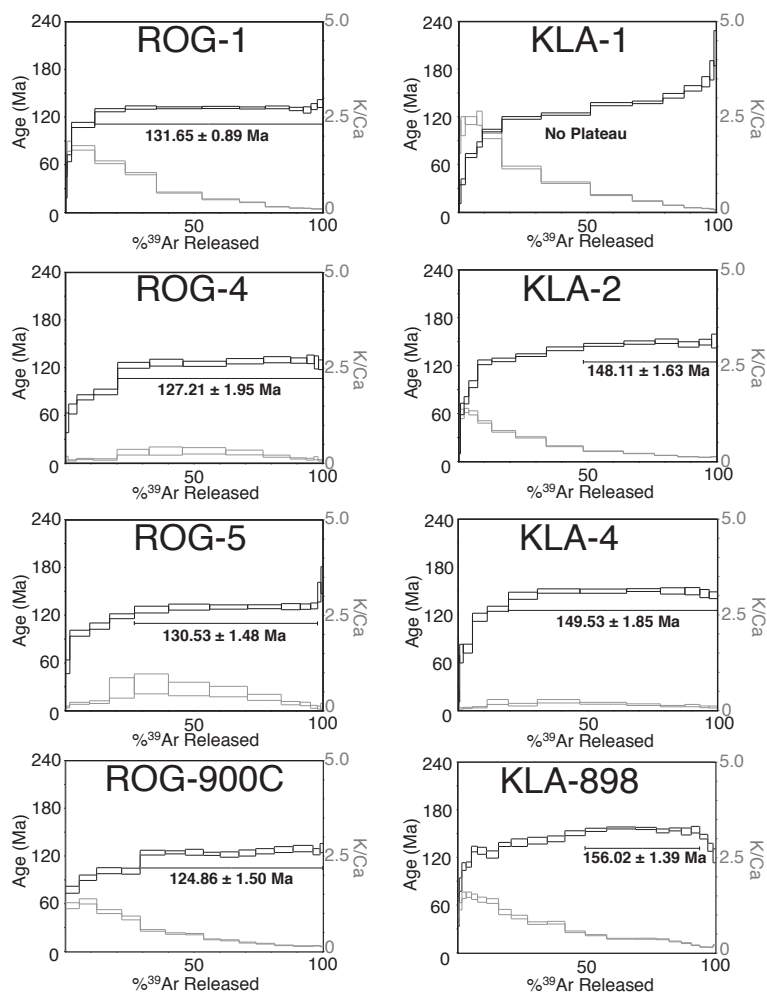


Figure 4 continued



## Southern Group

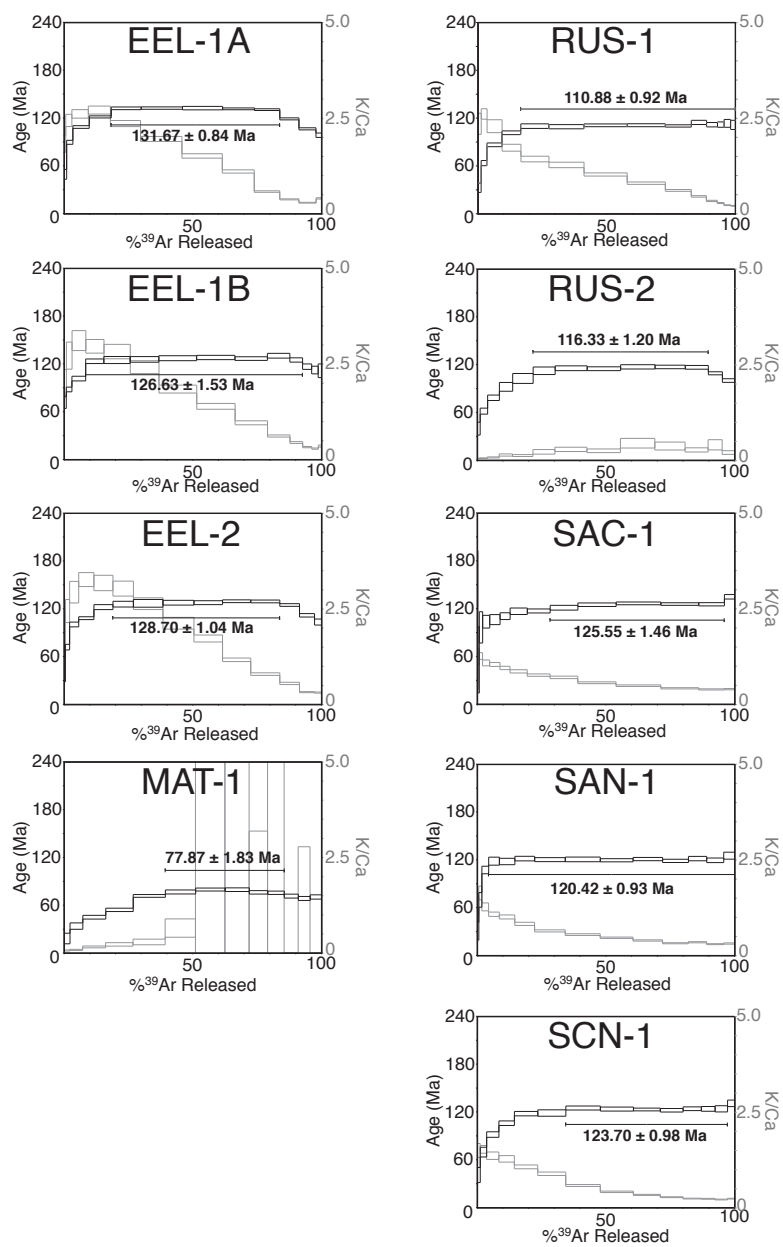


Figure 4 continued

*Background on Methods Used*

$^{40}\text{K}$  naturally decays to  $^{40}\text{Ar}$  by positron emission. This isotope system can be used to date potassium-bearing rocks. In order to reduce error in dating, it is possible to irradiate samples and measure Argon isotope ratios alone. Samples are irradiated in a reactor, which induces the reaction  $^{39}\text{K} \rightarrow ^{39}\text{Ar}$ . The ratio of  $^{40}\text{Ar}$  to  $^{39}\text{Ar}$  then reflects the time elapsed since the rock cooled below the temperature at which diffusion loss of Ar is insignificant (Stille et al., 1997). These isotope ratios can be measured very accurately using incremental heating. Rocks are slowly heated to their melting point in several discrete heating steps, and gasses are collected at each step.  $^{40}\text{Ar}$  can be lost from a sample over time through surface weathering, metamorphic events, chemical alteration, and mechanical grinding. In a rock or grain of sediment, the surface material may be influenced by alterations, but the innermost material within the grain will not. Altered surface material will melt and release gasses in the lower temperature heating steps. Later heating steps will release radiogenic  $^{40}\text{Ar}$  concentrations more representative of the crystallization age of the rock (VanLaningham et al., 2007). These later heat steps often produce similar ages, called the plateau age (see Figure 5 for further description). In the case of marine sediments,  $^{40}\text{Ar}/^{39}\text{Ar}$  dating can be used to determine the average time since cooling of all of the source rocks that the sediments eroded from. Sediments found at a given offshore site will have eroded from multiple bedrock sources on land, and any dating of those sediments will reflect the average ages of those terrestrial bedrock sources.

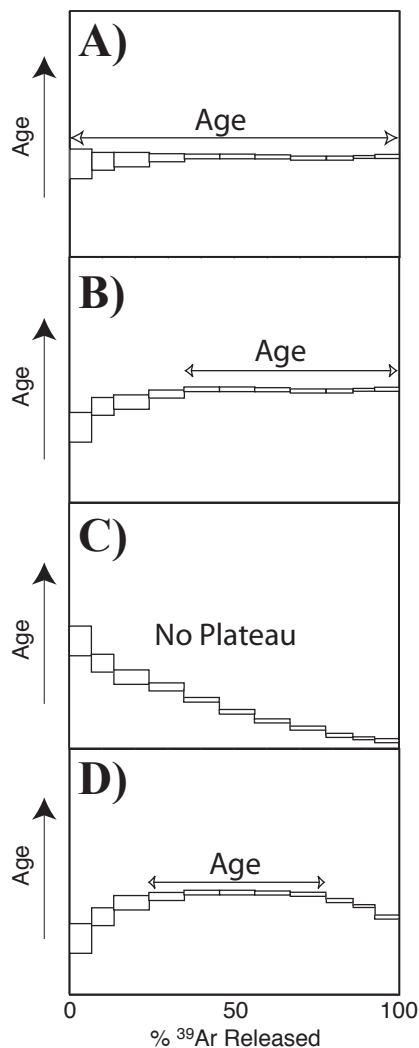


Figure 5: Typical  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  age spectra for: A) a single crystal degassing with a homogeneous distribution of argon or bulk sediment containing minerals of entirely the same age, B) argon loss from the surface of sediment grains through diffusion or the presence of young low-temperature minerals in bulk sediment samples, C) the presence of young high-temperature minerals, D) a combination of B and C, with younger low-temperature and high-temperature minerals.

Samarium (Sm) and Neodymium (Nd) are rare earth elements.  $^{147}\text{Sm}$  is radioactive and decays by alpha emission to the stable isotope  $^{143}\text{Nd}$ . The half-life of this decay is very long ( $1.06 \times 10^{11}$  years), so it is useful in dating terrestrial rocks (Stille et al., 1997).  $^{144}\text{Nd}$  is used as a reference isotope in this dating, because the number of  $^{144}\text{Nd}$  atoms in a unit weight of rock remains constant over time as long as the system is closed to Nd. The ratio of  $^{143}\text{Nd}$  to  $^{144}\text{Nd}$  will grow over time as more and more  $^{143}\text{Nd}$  is produced by decay of  $^{147}\text{Sm}$ . Studies of the isotopic ratios of meteorites suggest that the abundance of  $^{143}\text{Nd}$  on Earth and in the wider solar system has increased over time. The isotopic evolution of Nd in the solar system is described using the 'chondritic uniform reservoir' (CHUR) model. This model establishes a baseline for terrestrial Nd isotope ratios by describing their evolution through time in the wider solar system, based on meteorite data. Ratios of  $^{143}\text{Nd}/^{144}\text{Nd}$  are expressed as  $\epsilon_{\text{Nd}}$ , which is calculated based on deviations from CHUR. A positive  $\epsilon_{\text{Nd}}$  value indicates that rocks were derived material that was more recently removed from the mantle (i.e. younger crustal residence age) (Broecker et al, 1982). A negative epsilon value signifies that rocks were derived from old crustal rocks. The isotopic ratio of  $^{143}\text{Nd}/^{144}\text{Nd}$  in river sediments reflects the isotopic composition of the bedrock in the region drained by the river (Stille et al. 1997). River water has an important influence on the concentration and isotopic composition of marine Nd because seawater contains very little Nd (Stille et al., 1997). This means that the Nd found in marine sediments is largely derived from river-borne material and can be used as a provenance tool to identify and trace the terrestrial source of the sediment. Under most conditions the geochemical processes that take place during metamorphism, weathering, and sediment transport do not impact  $\epsilon_{\text{Nd}}$  values (Hemming et al, 1998). Because of the

diversity of source rock terrains found in the Pacific Northwest (with very different crustal residence ages) and the stability of Nd in the marine environment, bulk sediment  $\epsilon_{Nd}$  is a valuable tool in provenance studies for the region.

A similar provenance study has been conducted for glacio-marine sediments off the coast of Antarctica (Roy et al., 2007). That study combined bulk sediment  $\epsilon_{Nd}$  measurements with  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of individual hornblende grains in order to determine provenance of modern sediments surrounding Antarctica. It too sought to determine provenance of modern sediments as a base survey for future provenance work on older sediments, and found that the combined  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $\epsilon_{Nd}$  technique was very effective in doing so.

Radiolarian assemblages can be used to confirm that sediments are ‘modern’ - or have been deposited since the last glacial maximum (LGM). *Ceratospyris borealis* is a heterotrophic, single-celled spongy radiolarian that is well preserved in sediments due to the robust nature of its skeleton (Takahashi, 1997). During glacial intervals, it comprises 12-15% of the total radiolarian population in the NE Pacific. From LGM to 11.4 ka it decreased in abundance at a NE Pacific core site, and then completely disappeared from sediments deposited from 14.3-11.4 ka, indicating that core tops in this area that contain no *C. borealis* have been deposited in the last 12 ka (Pisias et al., 2001). This stratigraphic marker of the deglacial transition is found in a number of cores from the NE Pacific margin and should be easily identifiable in my array of cores (Sabin and Pisias, 1995).

*Site Description*

The Pacific Northwest margin (between 40°N and 45°N) is a region with high precipitation and low evaporation. Cool summertime sea-surface temperatures result from seasonal upwelling and coastal fog that keep the coastal climate cool in summer (Pisias, 2001). The natural vegetation is moist coniferous lowland forests, characterized by western hemlock and sitka spruce. Away from the coastal fog, the inland is warmer and drier and is dominated by oak woodlands and grasslands. The western slopes of the Cascades volcanic arc are covered by coniferous forests of fir and hemlock

The region has a significant seasonal pattern of surface winds (Huyer, 1983). This pattern is driven by movement of the North Pacific high-pressure cell system. In summer, the high-pressure system causes strong coastal upwelling associated with high biological productivity and a strong southward flowing eastern boundary current, the California current (Sabin et al., 1995). In winter, the Aleutian low-pressure cell displaces the North Pacific high-pressure system to the south, causing predominantly onshore winds and a northward flowing Davidson current (Pisias, 2001). A relatively large number of small rivers in the Pacific Northwest discharge sediments onto a narrow, energetic continental shelf. The transport of this sediment is very episodic, dominated by storm events between December and March (Wheatcroft et al., 2005). In general, this region has relatively high sediment production and active continental shelf sediment accumulation. Aeolian (wind borne) input of dust into marine sediments is minimal (Walter et al., 2000).

River discharge and sediment loads from the Pacific Northwest vary widely (Karlin, 1980, VanLaningham, 2007). With a discharge of over 216 km<sup>3</sup>/yr, the Columbia is the region's largest freshwater input, releasing over 20 times more water into the

northeast Pacific than the second largest river, the Rogue. Interestingly, however, the Eel river of northern California is the region's largest sediment source (see Table 1). Dams on the Columbia have likely reduced the river's sediment load by at least 50% (Sherwood et al., 1990).

Table 1: Characteristics of rivers in the Pacific Northwest

<b>River</b>	<b>Basin size (km<sup>2</sup>)</b>	<b>Avg Discharge (km<sup>3</sup>/yr)</b>	<b>Avg annual load (x10<sup>3</sup> kg)</b>	<b>Sed Yield (x10<sup>3</sup> kg/km<sup>2</sup>/yr)</b>
Quinalt	684	2.6	0.1	125
Grays Harbor	5776	8.1	0.7	114.5
Willapa Bay	1046	1.9	0.1	125
Columbia	661211	216	5	7.6
Tillamook Bay	1400	2.7	0.2	125
Siletz	523	1.4	0.1	125
Yaquina	665	1	0.1	128.8
Alsea	865	1.5	0.1	75
Siuslaw	1523	1.8	0.1	62
Umpqua	9534	6.7	0.1	147
Coos	1567	2.7	1.4	150
Coquille	1960	2.2	0.2	150
Rogue	13394	10.1	0.3	170
Chetco	702	2.3	0.2	250
Smith	1590	3.3	0.4	252
Klamath	21950	7.3	3.3	150
Redwood	720	0.9	1.3	1805
Mad	1256	1.3	2.6	2070
Eel	8063	6.6	18	2232
Mattole	635	1.1	1.3	2000
Navarro	785	0.5	0.2	300
Gualala	901	0.4	0.3	300
Russian	3452	2.4	1.1	318

The Pacific Northwest region is characterized by a diverse set of geologic provinces. In Washington, the Quinalt River drains the Olympic Mountains, which are comprised of a suite of sandstones, mudstones, and volcanic lithologies that have Eocene

to Miocene depositional ages (Brandon and Vance, 1992). The Chehalis, Willapa Bay, and Tillamook Bay rivers of the coastal range of southwestern Washington and northwestern Oregon erode Eocene sedimentary and volcanic rocks (Walker and MacLeod, 1991). The Columbia River has an immense drainage basin, and erodes a diverse set of lithologies. Its northern tributaries in British Columbia erode Mesozoic accreted terrains of sedimentary, volcanic, and plutonic origins, as well as intrusions (Ghosh, 1995; Monger et al., 1982). Other tributaries erode Cretaceous rocks of the Idaho-Bitterroot Batholith granites, Tertiary volcanic rocks, Mesozoic and Paleozoic meta-sedimentary rocks. The primary channel of the Columbia erodes a vast area of Miocene Columbia River Basalts and Tertiary to modern arc volcanic rocks of the Cascades (VanLaningham, 2007). The Coos River of southern Oregon drains Eocene turbidite sequences and oceanic basalt. The Umpqua River drains Cenozoic basalts and andesites, as well as turbidite sequences of the Coast Range. The Rogue and Klamath Rivers drain Mesozoic accretionary complexes, composed of metasedimentary, meta-volcanic, granitic, and gabbroic rocks and ophiolitic sequences, as well as the southern cascade arc (VanLaningham, 2007). The Eel, Mattole, and Russian Rivers of northern California drain a Cretaceous to Tertiary sequence of sandstones and mudstones (McLaughlin et al., 1994). The Sacramento and San Joaquin Rivers drain granitic rocks of the Mesozoic Sierra Nevada Mountains. This diverse source rock geology means that each river produces a unique mixture of sediments that it discharges into the ocean.

A regional climate model, RegCM2, has been developed by the US Geologic Survey and has been run for the region. It is based on the standard version regional climate model (RegCM) described by Giorgi et al (1993) and was run using lateral



boundary conditions predicted by the GENESIS atmospheric general circulation model, which provides simulations of large-scale atmospheric circulation (Hostetler et al., 1999). The model has been run at 60km and 10km spacing over western North America and can be used to infer vegetation responses, glacier mass balance, surface water balance, lake levels, and coastal upwelling. Output from the RegCM2 that includes relevant surface processes (i.e. hydrology and vegetation feedbacks) could be used to model climate-induced changes in streamflow and terrestrial vegetation distributions that combine to deliver pollen to the marine system (Pisias et al., 2006). By comparing provenance data with model results, we should be able to both assess whether the marine pollen record faithfully reflects climate-induced changes in the distribution of terrestrial vegetation, as well as test the model itself for accuracy.

## METHODS

Sediments from Pacific NW margin sites used in this project were sampled from Oregon State University's Marine Geology Core Repository. We selected fourteen cores based on location, away from LGM river canyons (which are more likely to see sediment disruption from storm and earthquake events) (see Figure 6 for locations of cores used). Sample preparation and irradiation followed the procedures of VanLaningham et al. (2006). Radiolarian slides were made following the procedure of Roelofs and Pisias (1986). We rinsed samples with hydrogen peroxide and hydrochloric acid to remove carbonate and organic matter. Microfossils were plated using Stokes settling, and the remaining liquid was aspirated. We used the taxonomy of Nigrini and Moore (1979) to identify radiolaria. We counted individual *C. borealis* on slides, and estimated total radiolarian number in order to determine the percent *C. borealis*. If the percent of *C. borealis* present was less than 15%, the sample was assumed to be modern. In addition, samples were scanned for pre-Pleistocene radiolaria to determine if older material was present.

We extracted the 20-63  $\mu\text{m}$  size fraction from 100-300g of bulk sample material by sieving at 63  $\mu\text{m}$  and removing the 0-20  $\mu\text{m}$  fraction using Stokes settling. Samples were then rinsed with sodium acetate for carbonate removal, a sodium dodecyl sulfate reagent for organic removal, and a sodium citrate reagent for oxyhydroxide removal.

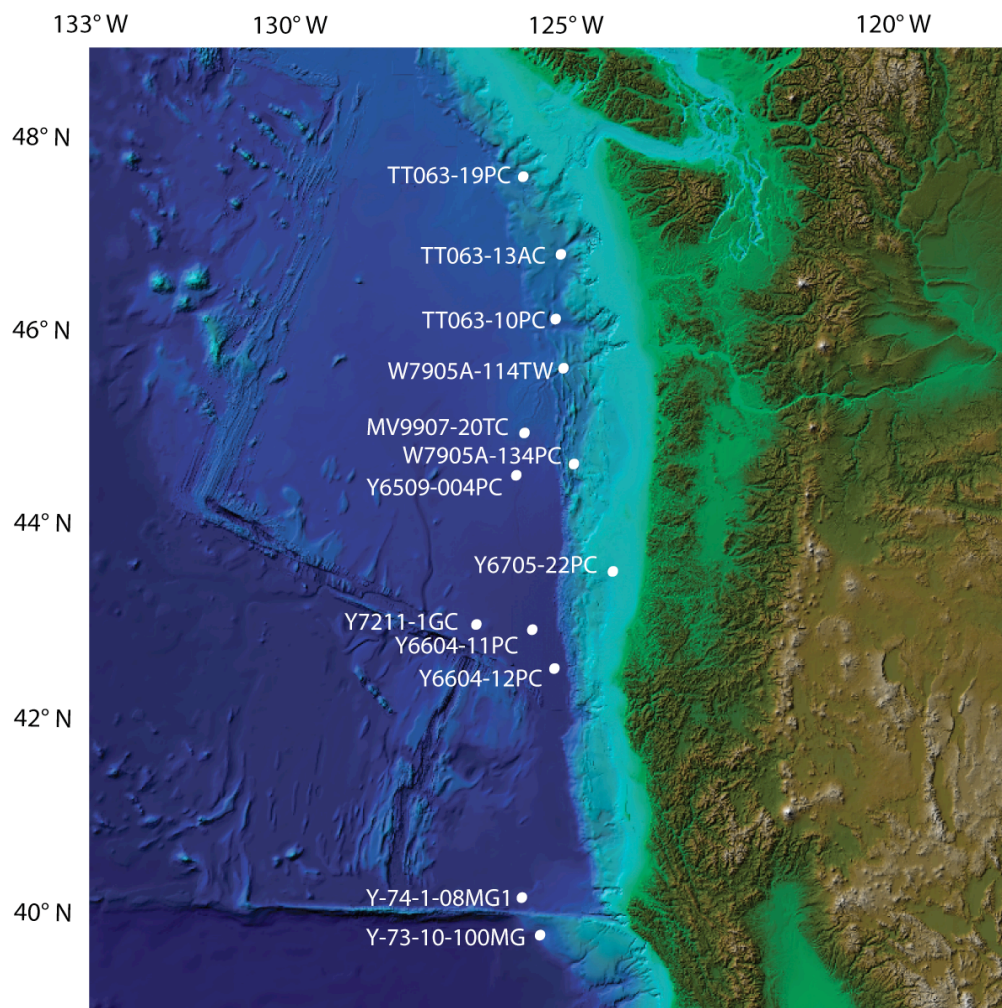


Figure 6: Location of 14 marine sediment cores, for which youngest layer (core top) has been analyzed for radiolaria assemblage, bulk Ar-age, and  $\epsilon\text{Nd}$  of 20-63  $\mu\text{m}$  size fraction.

We irradiated samples with the FCT-3 monitor standard for 6 hours near the core of the 1MW TRIGA reactor at Oregon State University. These irradiated samples were then analyzed in the geochronology lab at OSU using the MAP 215-50 mass spectrometer. We loaded samples in a Cu sample holder, placed them in a vacuum chamber, and heated them in 10 incremental temperature steps, from 400°C to a fusion point at 1400°C with a defocused 10W CO<sub>2</sub> laser. The laser was programmed to traverse

the sample during a given 5-minute heating step. At each heating step, Zr-Al getters were used to remove active gases from the extracted Ar. A five-minute pump out time was used between samples to ensure that there was no contamination. Concentrations, measured as beam currents, were measured for isotopes  $^{40}\text{Ar}$ ,  $^{39}\text{Ar}$ ,  $^{38}\text{Ar}$ ,  $^{37}\text{Ar}$ , and  $^{36}\text{Ar}$ . The latter three were used in corrections for atmospheric contamination and reactor-induced interferences, following the procedures described by McDougall and Harrison (1999). We calculated the plateau ages and reduced the data using the Excel software program ArArCalc (Koppers, 2002). Plateau ages are defined as a consecutive sequence of concordant heating steps ages, comprising more than 50% of its total  $^{39}\text{Ar}$  released in the sample (VanLaningham et al., 2007; Koppers, 2002). K/Ca ratios were calculated from measured  $^{39}\text{Ar}$  and  $^{37}\text{Ar}$  concentrations.

This  $^{40}\text{Ar}/^{39}\text{Ar}$  procedure was repeated on three non-marine samples; river sediments were collected from the Fraser River in order to increase the northward extent of VanLaningham's 'fingerprinted' rivers.

$\epsilon_{\text{Nd}}$  was calculated following the procedure of VanLaningham (2007). We digested samples in Teflon beakers with concentrated HF and  $\text{HNO}_3$ . Samples were converted to chlorides by drying down in 6N HCl and bringing them back up in 2.5N HCl. This 'drying down' procedure was repeated three times. We then passed samples through a Dowex AG50X8 cation exchange column followed by an Eichrom In-spec resin chromatography column. This separated Nd from the other elements. We analyzed samples in OSU's Keck collabratory on the Nu multi-collector inductively coupled plasma mass spectrometer.

## RESULTS

All of the samples had percentages of *C. borealis* less than 15% (see Table 2). We determined that core Y73-10-100MG was deposited during the Pleistocene (i.e. much older than the other samples) based on the abundance of the radiolaria species *Lamprocyrtis heteroporus*.

Generally, modern marine sediment samples just off the shelf break were found to reflect proximal river sediment sources, with a net northward trend in sediment deposition. The following section will discuss individual core results in the context of their potential river sources. My results are summarized in Figure 7 (Ar/Ar plots), Figures 8-20 ( $\epsilon_{\text{Nd}}$  vs.  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages for sediments and rivers), and Table 3 (summary of results).

Table 2: Radiolaria species composition in PNW core tops, specifically % *C. borealis*

<b>Core:</b>	<b>% <i>C. borealis</i></b>
TT063-19PC	0 0
TT063-13AC	0.63 0.034
TT063-10PC	0 0.036
W7905A- 114TW	0.017 0
MV9907-20TC	0 0
W7905A-134PC	0 0
Y6509-004PC	0 0
Y6705-22PC	0 0
Y6604-11PC	0 0
Y7211-1GC	0 0
Y6604-12PC	0 0
Y74-1-08MG	0 0
Y73-10-100MG	0.37 0

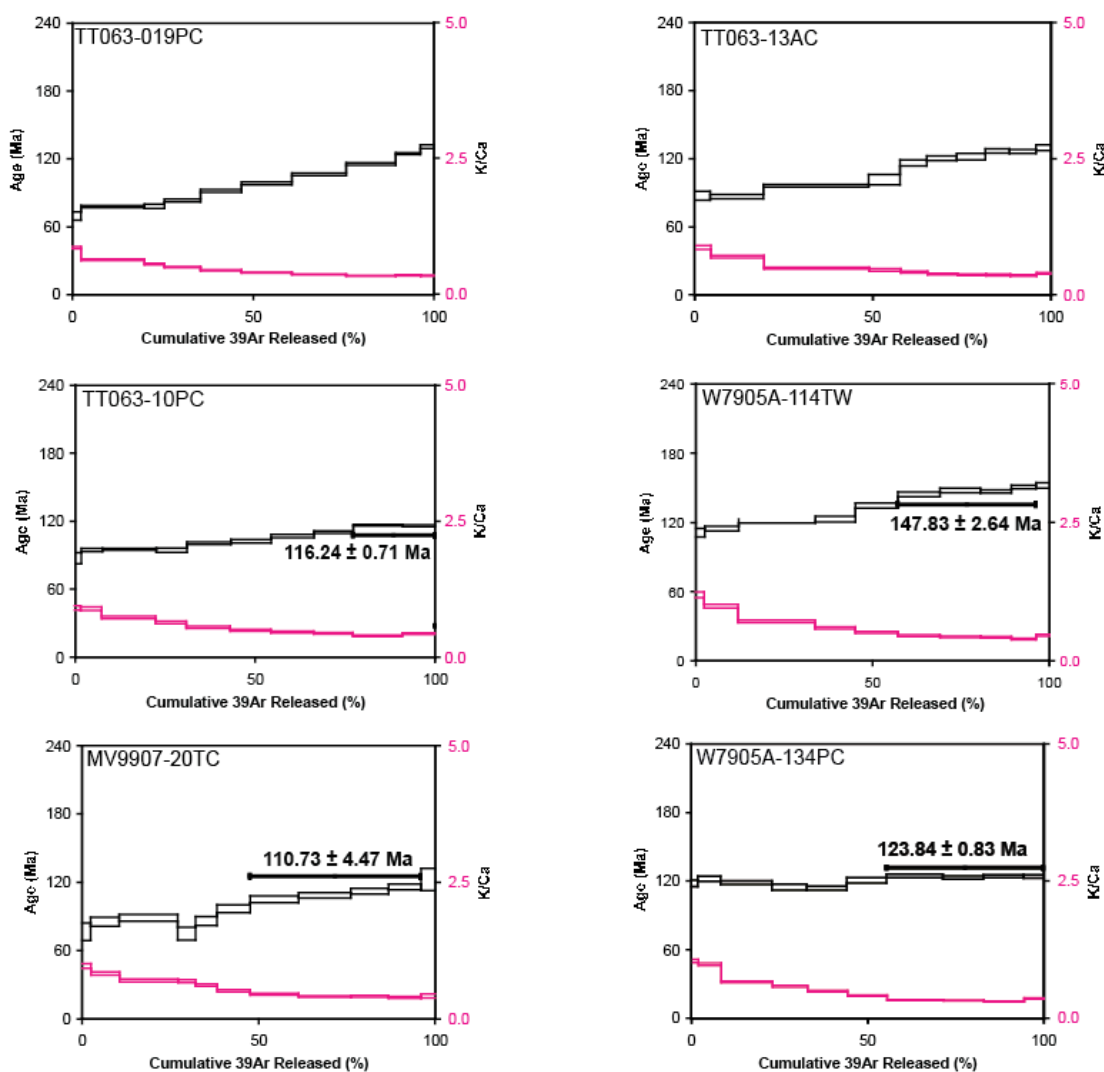


Figure 7:  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating spectra and K/Ca spectra (in pink) for Pacific Northwest marine sediment core top array. Analytical uncertainties (2-sigma) related to age and K/Ca are depicted by vertical scaling of each step-heating box

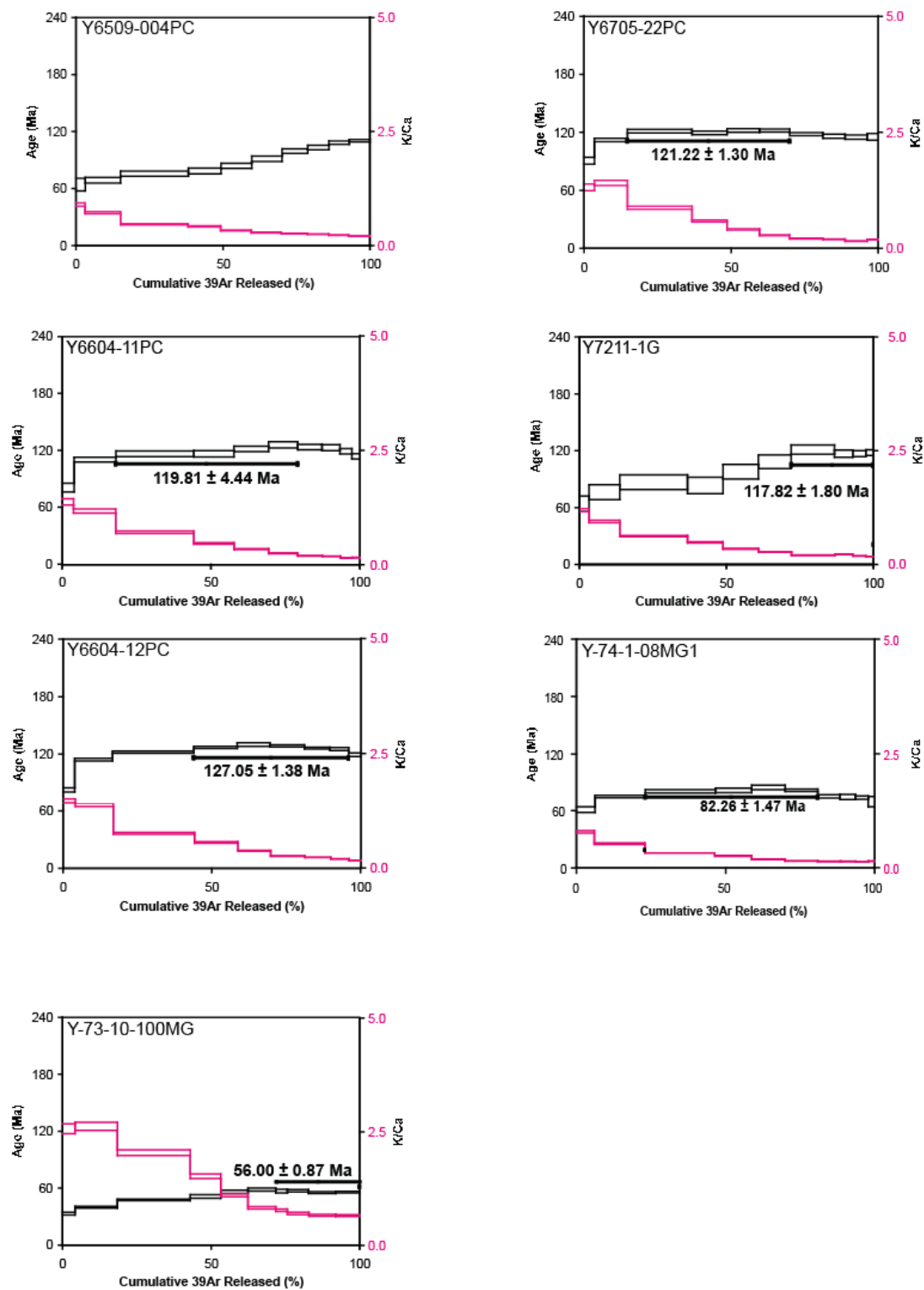


Figure 7 continued



Table 3: Summary of core locations and results

<b>Core</b>	<b>Latitude</b>	<b>Longitude</b>	<b><math>^{40}\text{Ar}/^{39}\text{Ar}</math> Plateau Age</b>	<b>+/- 2<math>\sigma</math></b>	<b><math>\epsilon\text{Nd}</math></b>	<b>+/- 2<math>\sigma</math></b>
TT063-19PC	47.91	125.901	n/a	n/a	-6.32	0.055
TT063-13AC	47.142	125.28	106.14	0.85	-7.78	0.053
TT063-10PC	46.57	125.29	116.24	0.71	-9.88	0.078
W7905A-114TW	46.11	125.248	147.83	2.64	-30.57	0.052
MV9907-20TC	45.38	125.785	110.73	4.47	-6.17	0.054
W7905A-134PC	45	125.155	123.84	0.83	-	-
Y6509-004PC	44.95	125.787	86.15	1.01	-4.87	0.085
Y6705-22PC	43.853	124.662	121.22	1.3	-4.59	0.06
Y6604-11PC	43.28	125.522	119.81	4.44	-2.34	0.056
Y7211-1GC	43.257	126.377	117.82	1.8	-13.53	0.074
Y6604-12PC	42.833	125.4	127.05	1.38	-2.82	0.054
Y74-1-08MG	40.422	125.517	82.26	1.47	-4.02	0.056
Y73-10-100MG	40.032	125.298	56	0.87	-6.94	0.054

*TT063-19PC and the Fraser River*

This core, located just off the shelf break of northern Washington, had an  $\epsilon_{\text{Nd}}$  of -6, reflecting the high input of Columbia river sediments to the site (see Figure 8). The sediments at this site did not form a plateau during  $^{40}\text{Ar}/^{39}\text{Ar}$  dating (see Figure 7). The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages released during successive heat steps range from 69.4-130.8 million years (Ma). The Columbia River, located south of the core site, carries sediments that sometimes do not form plateaus (see Figure 4, sample COL-1498), or form a characteristic double plateau (see Figure 4, sample COL-3). The range of ages released during heat steps at site TT063-19PC are similar but somewhat lower than the range of ages released during heat steps of sample COL-1498. This reflects an input of Fraser River sediments to the site. The Fraser River sediments were collected and analyzed in order to help understand the provenance of the sediments at site TT063-19PC. We found that the river carries sediments into the ocean with  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages of 108, 125, and 129 million years. The lowest value of 108 Ma helps explain why the sediments at this core site appear to be somewhat younger than the Columbia River sediments: the site receives sediments from the Fraser River as well (see Figure 8).

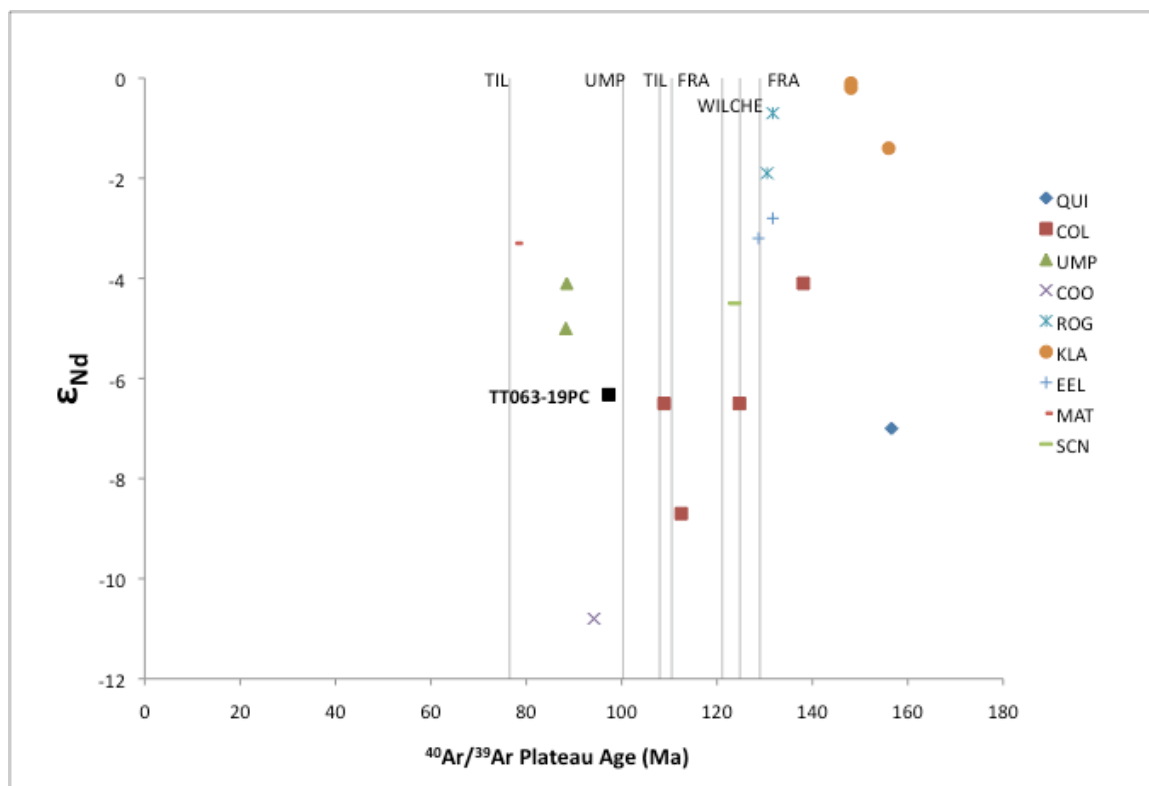
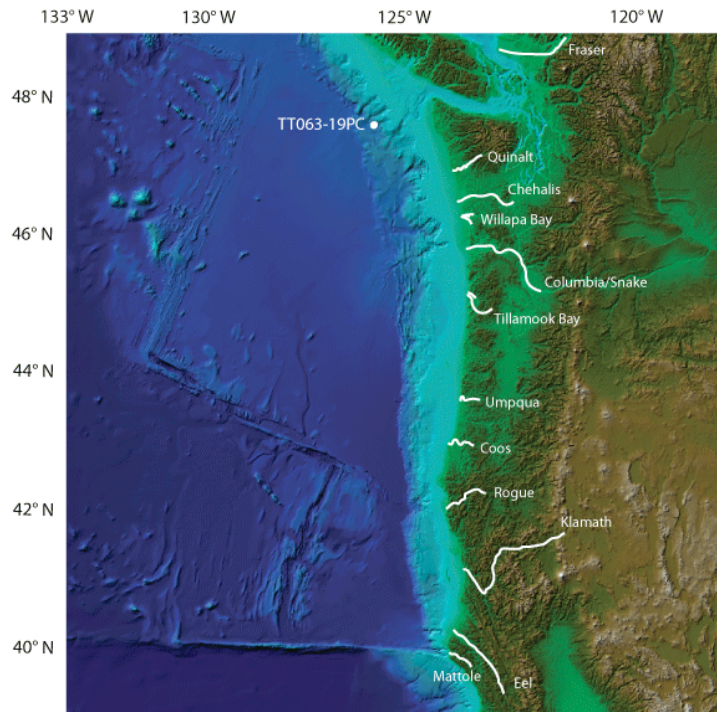


Figure 8:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core TT063-19PC and proximal river sediment sources. Vertical lines reflect the  $^{40}Ar/^{39}Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary sources of the sediments are the Columbia and the Fraser Rivers.



*TT063-13AC*

This core is located off the coast of central Washington (see Figure 9). It is composed of sediments from the Columbia, with additional input from the Tillamook Bay. The  $\epsilon_{Nd}$  range reflects the Columbia sediments, and the Ar/Ar plateau age is within the range of both the Tillamook Bay rivers and the Columbia (the  $\epsilon_{Nd}$  of the Tillamook Bay rivers is unknown). The contribution from the proximal Quinalt River is minimal.

*TT063-10PC*

This core is located near the mouth of the Columbia River, and is primarily composed of Columbia River sediments (see Figure 10). It has a similar plateau age, shape, and K/Ca ratio as the Columbia River sediments. It does not show the characteristic ‘double plateau’ that some of the Columbia River sediments exhibit, however (see Figure 4, sample COL-3). The  $\epsilon_{Nd}$  of the TT063-10PC sediments is much lower than the Columbia River sediments, indicating that there is another sediment source for the core as well. The Coos River in southern Oregon has a similarly low  $\epsilon_{Nd}$  value. While it seems unlikely that Coos sediments were transported so far north, it is possible that this long-ranging transport does occur, particularly given that Coos sediments do not appear at proximal cores (see Y6604-11PC).

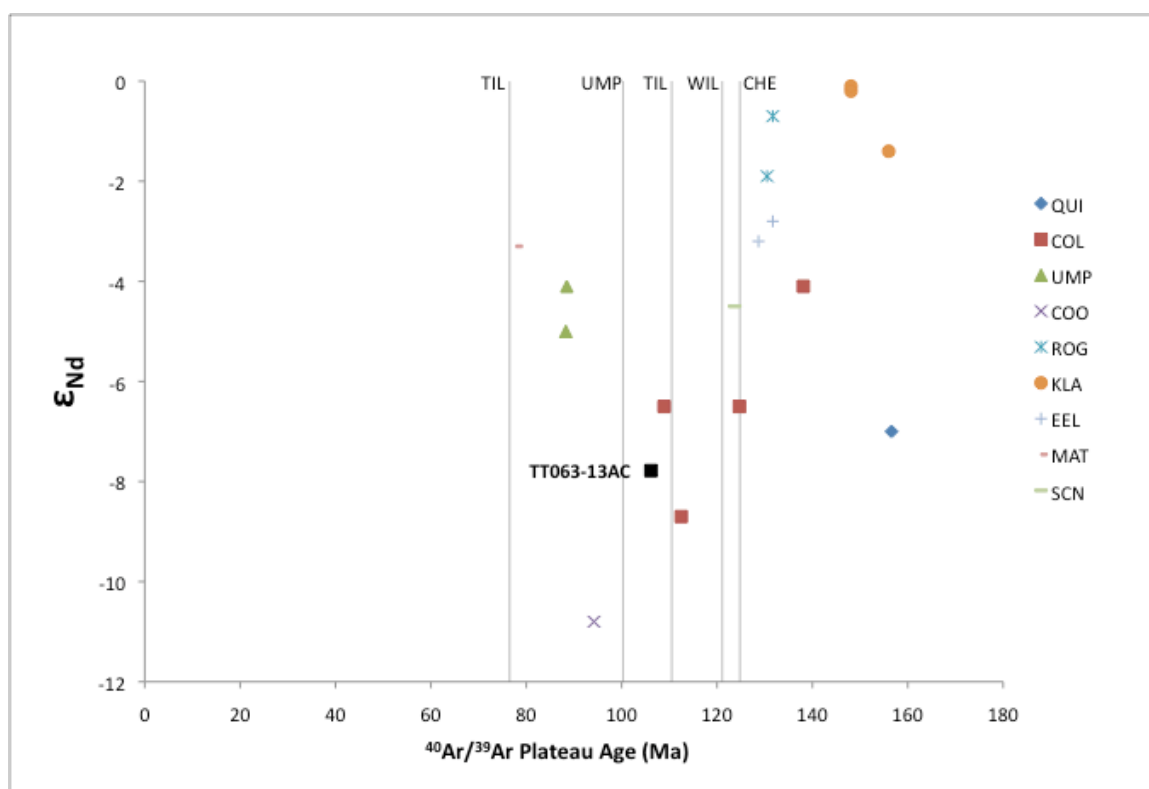
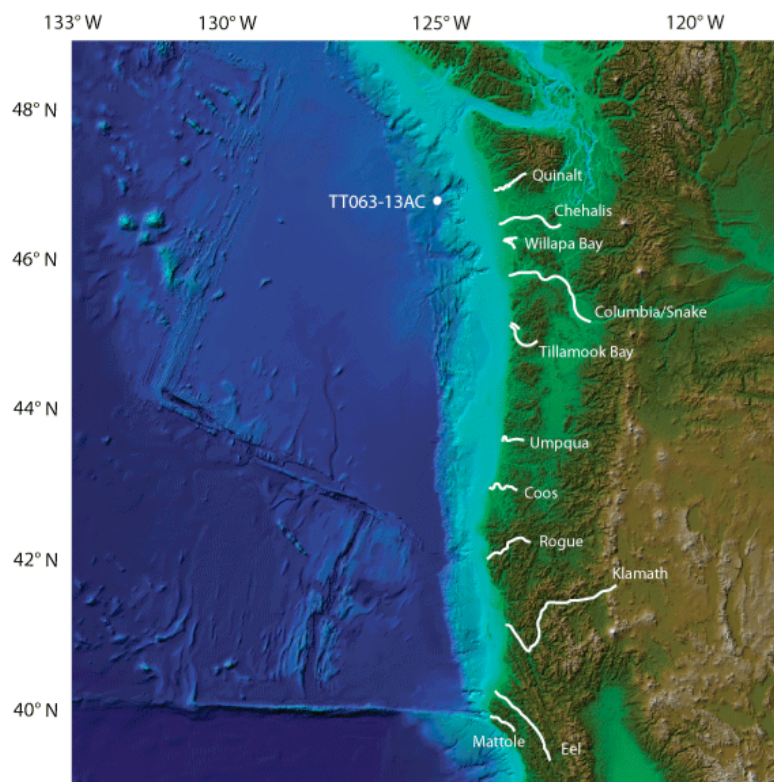


Figure 9:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age and  $\epsilon_{\text{Nd}}$  of sediment core TT063-13AC and proximal river sediment sources. Vertical lines represent the Ar/Ar plateau age of rivers whose  $\epsilon_{\text{Nd}}$  was not measured. The primary source of the sediments is the Columbia River, with additional input from the Tillamook Bay. The contribution from the Quinalt River is minimal.



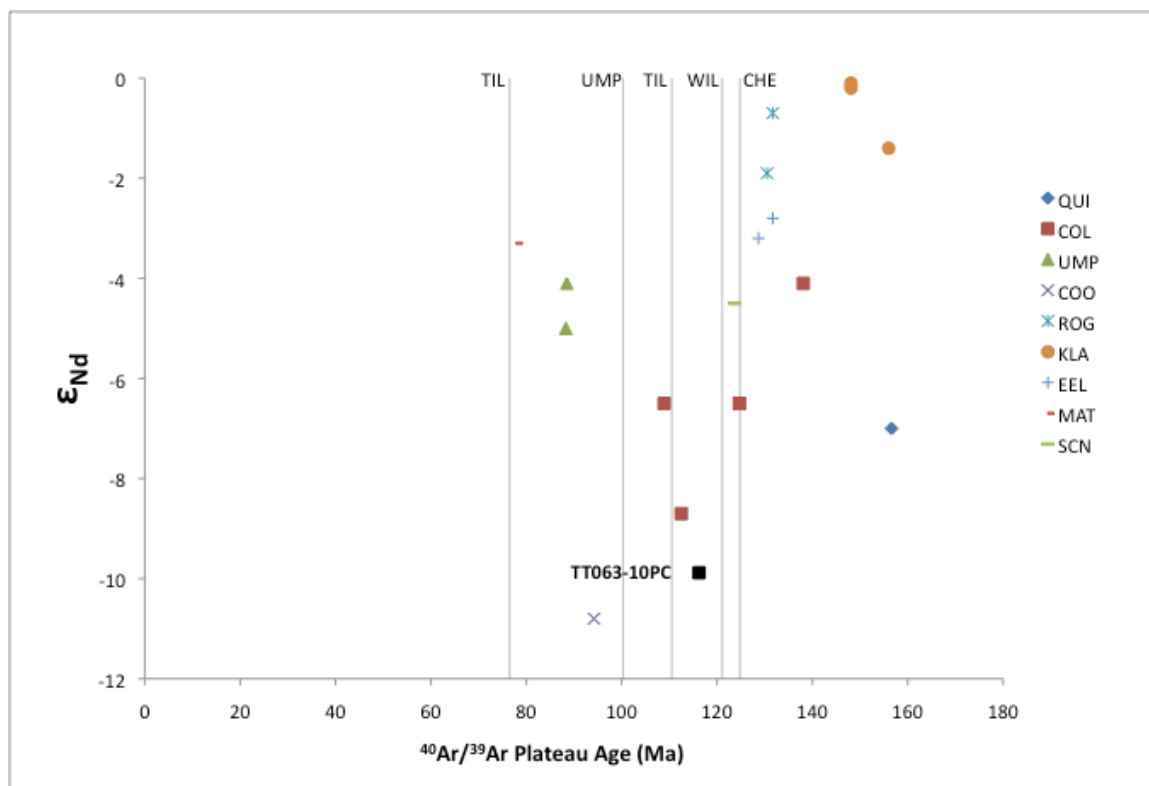
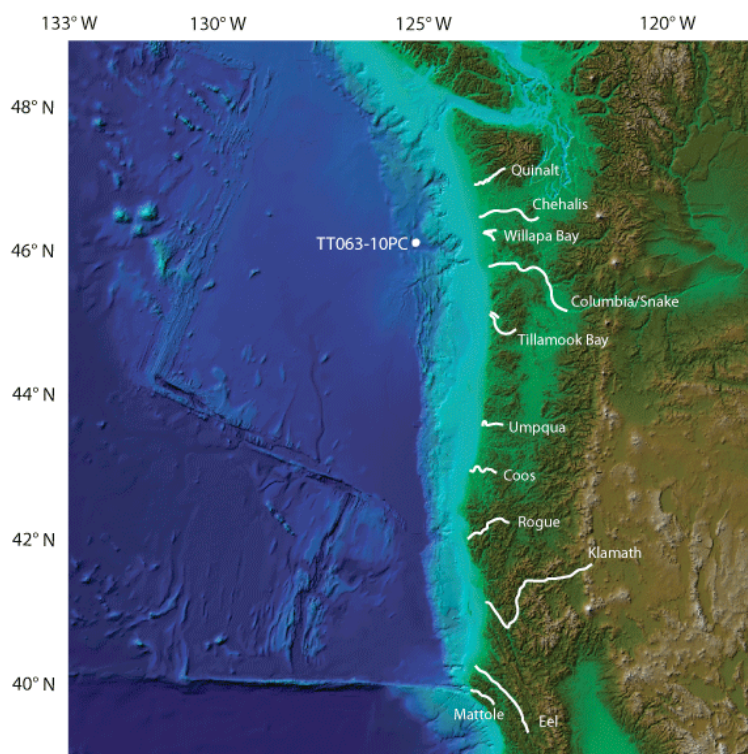


Figure 10:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age and  $\epsilon_{\text{Nd}}$  of sediment core TT063-10PC and proximal river sediment sources. Vertical lines reflect the Ar/Ar plateau age of rivers whose  $\epsilon_{\text{Nd}}$  was not measured. The primary sources of the sediments are the Columbia and Coos Rivers.



*W7905A-114TW*

This core is located just offshore of the LGM channel of the Columbia (see Figure 11). The  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of the core suggests that it is composed of Columbia and Quinalt River sediments. The  $\epsilon_{\text{Nd}}$  of the core is anomalously low, however, indicating experimental error. There are no source terrains in western continental North America with an  $\epsilon_{\text{Nd}}$  of  $-30$ . The sources of experimental error that could have caused this anomaly will be discussed later in detail.

*MV9907-20TC*

This core is located offshore of the Tillamook Bay. It is composed of Columbia River sediments and Tillamook Bay sediments (see Figure 12). Without knowing the  $\epsilon_{\text{Nd}}$  of Tillamook Bay sediments, it is difficult to know the percent composition of Tillamook vs. Columbia River sediments at the site. By comparing the annual sediment load of the two rivers, we can assume that there is a greater amount of Columbia River sediments at the location (see Table 2). The Columbia discharges  $5 \times 10^3$  kg of sediment per year into the ocean, while the Tillamook Bay rivers discharge only  $0.2 \times 10^3$  kg of sediment per year.



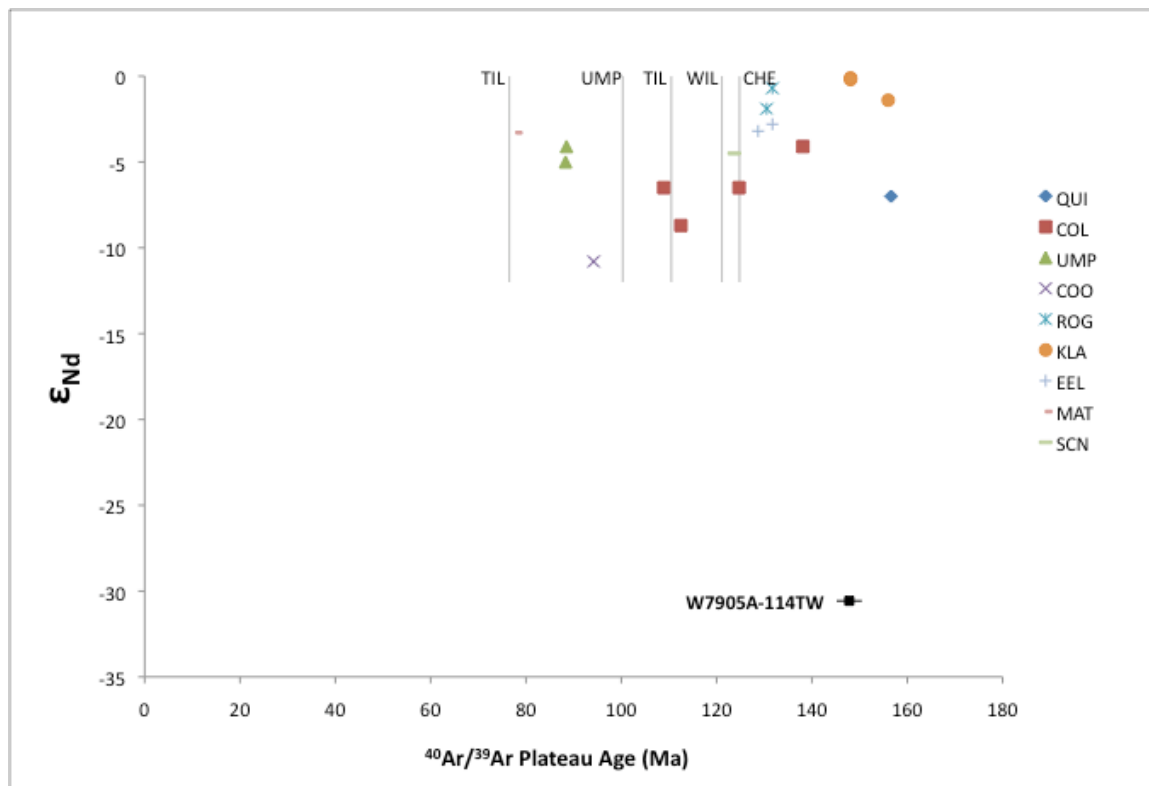
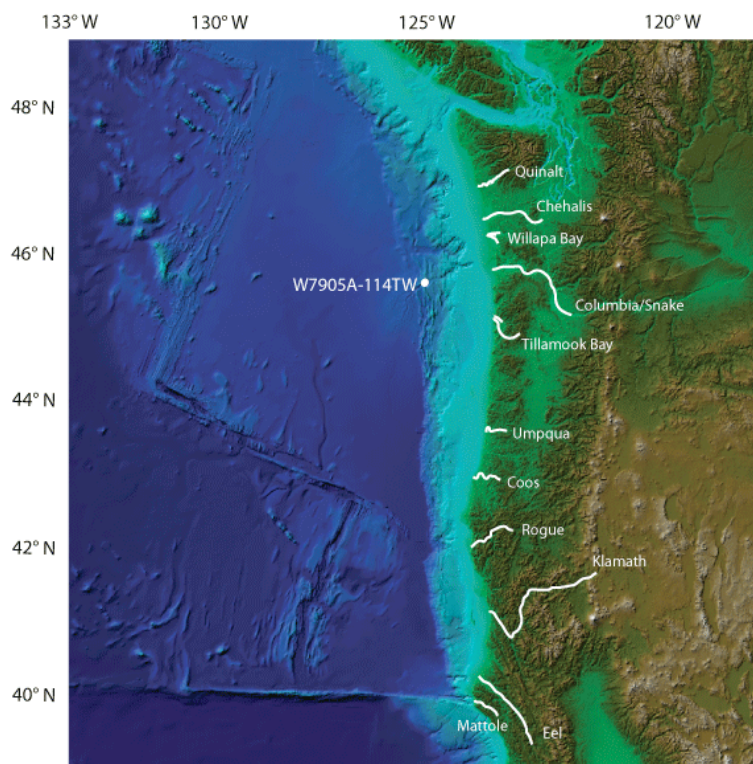


Figure 11:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core W7905A-114TW and proximal river sediment sources. Vertical lines represent the  $Ar/Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The  $^{40}Ar/^{39}Ar$  plateau age of the core suggests that it is composed of Columbia and Quinalt River sediments. The  $\epsilon_{Nd}$  of the core is anomalously low, indicating experimental error.





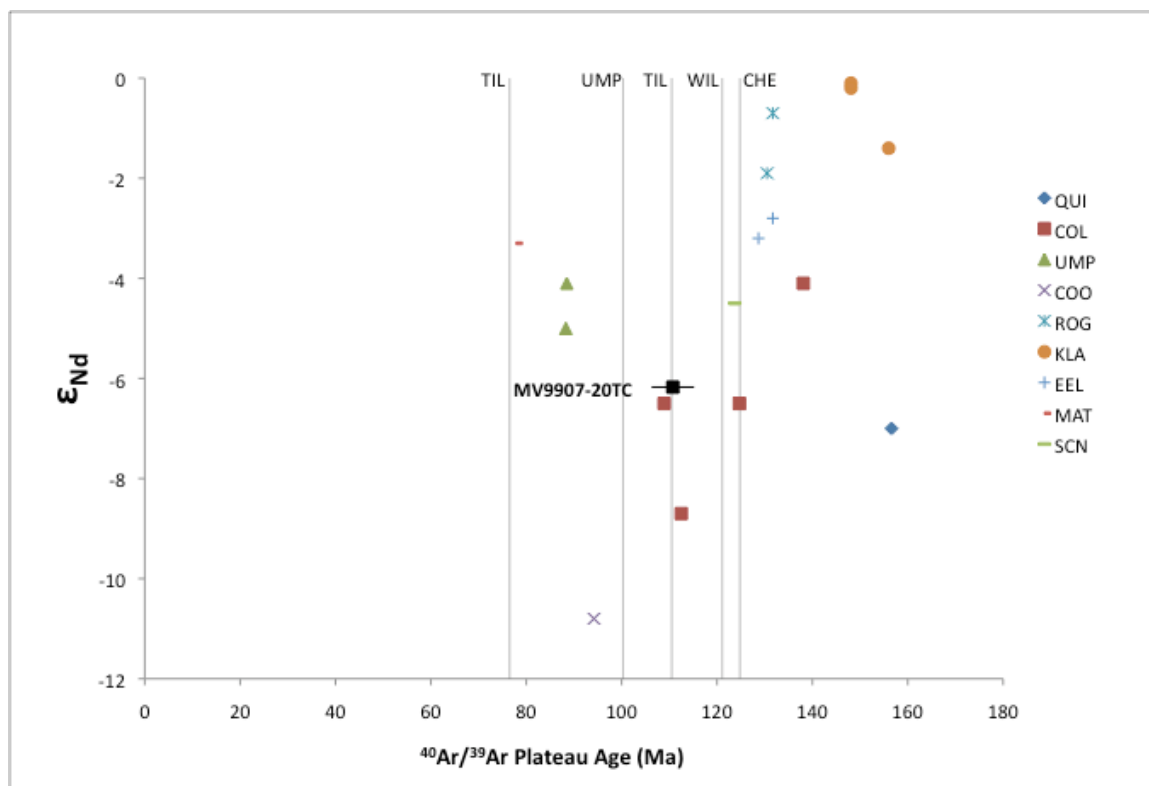
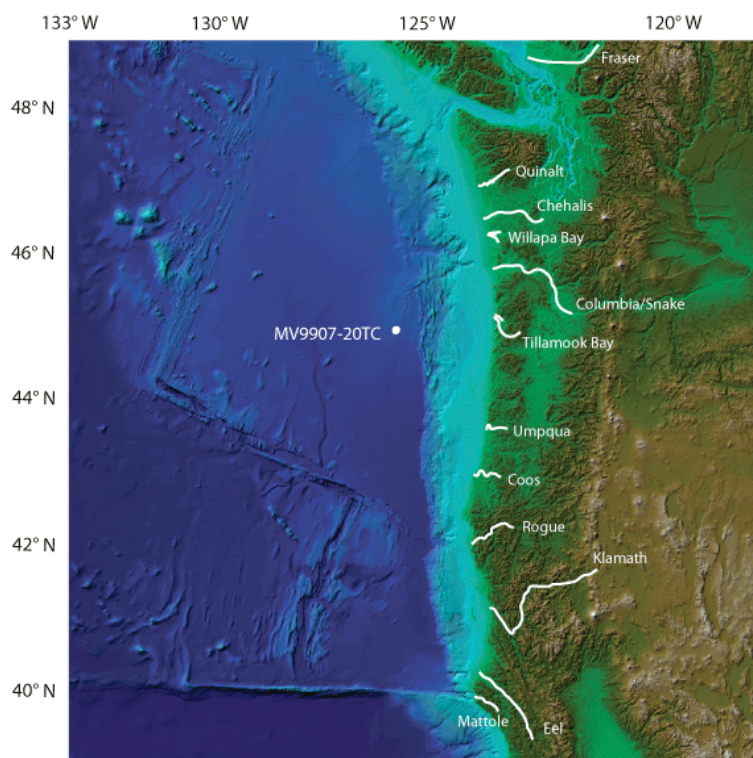


Figure 12:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core MV9907-20TC and proximal river sediment sources. Vertical lines represent the Ar/Ar plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary source of the sediments is the Columbia River, with contributions from the central coast range rivers (Tillamook and Willapa Bay rivers).



*Y6509-004PC*

This core is located off central coast of Oregon. It is primarily composed of Umpqua River sediments, with a small input of Tillamook Bay sediments (indicated by the  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages slightly younger than those of the Umpqua River) (see Figure 13).

*W7905A-134PC*

Only  $^{40}\text{Ar}/^{39}\text{Ar}$  dating was performed on this core, located just offshore of the Columbia/Snake River mouth (see Figure 14). The black vertical line shows the measured plateau age at 125.15 ma). The sediments do not show a double plateau age that is associated with some Columbia River sediments, but the plateau age indicates that there is a high concentration of Columbia sediments. Specific provenance of the sample could be more accurately determined if the  $\epsilon_{\text{Nd}}$  of the core top was known.

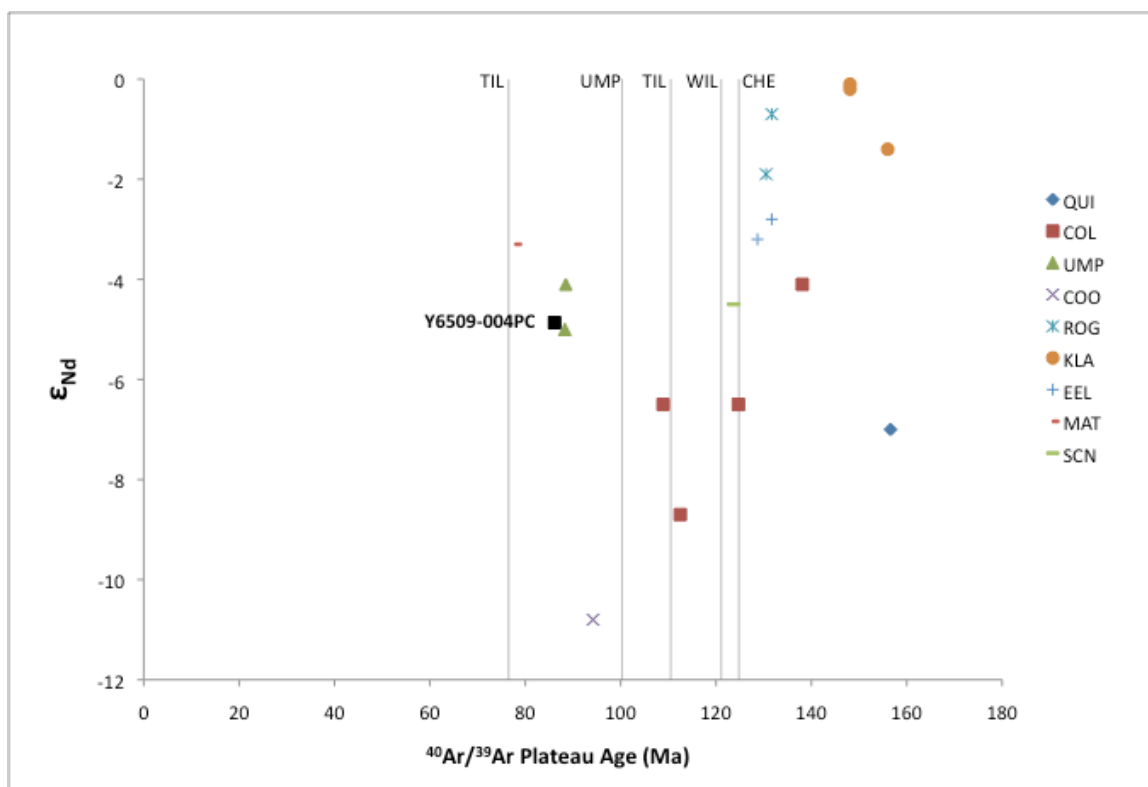
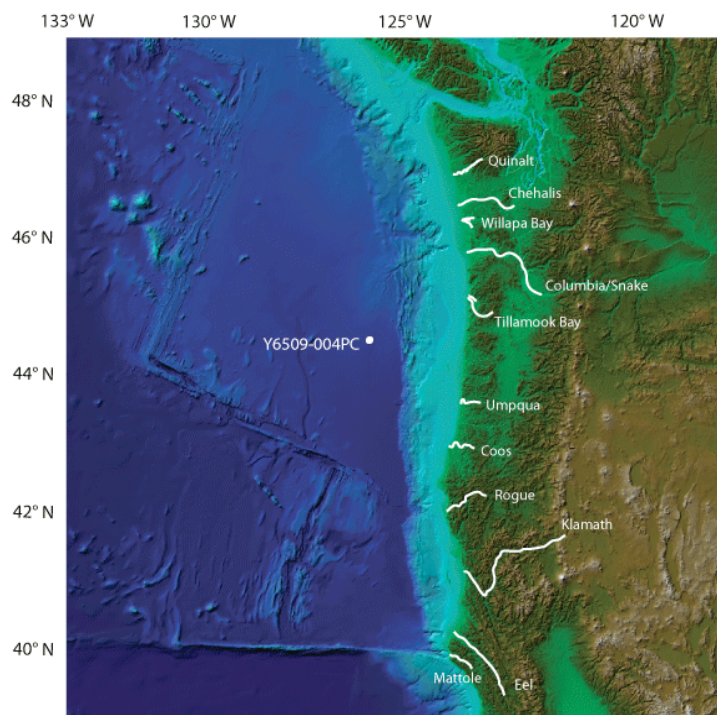


Figure 13:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core Y6509-004PC and proximal river sediment sources. Vertical lines represent the  $Ar/Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary river source of the sediments is the Umpqua, with limited input from the Tillamook bay rivers.



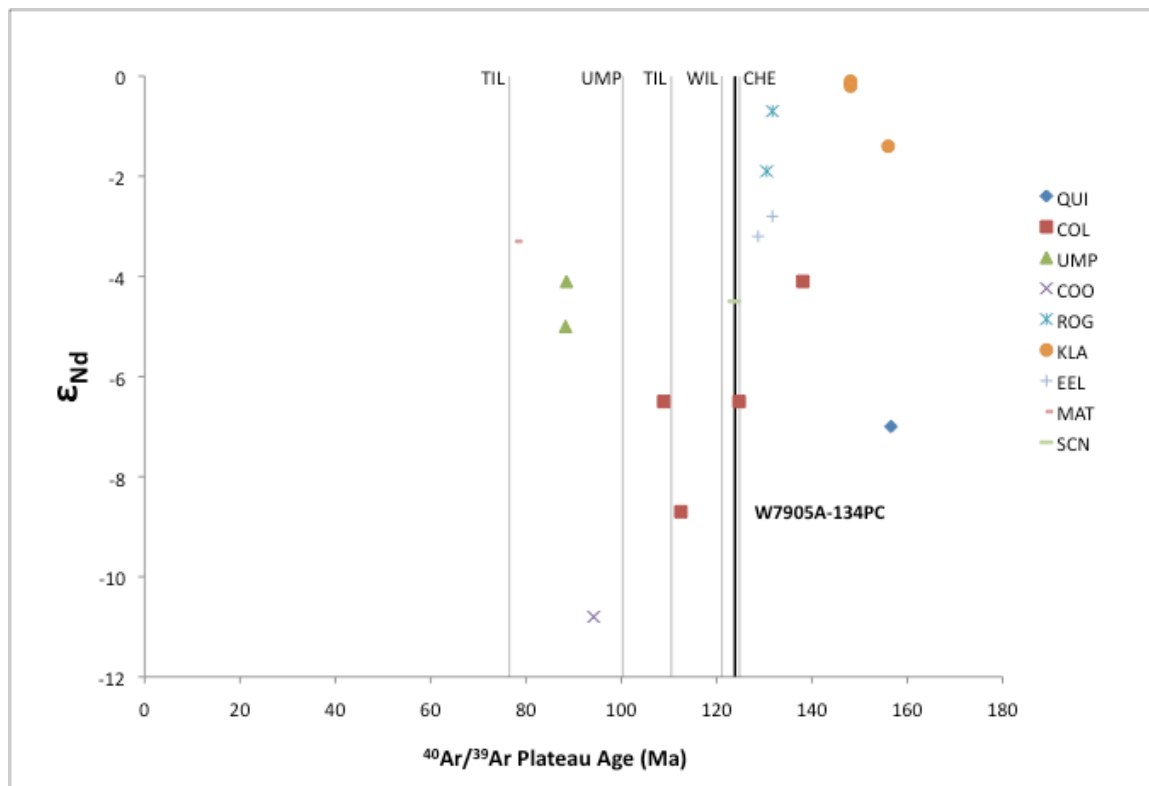
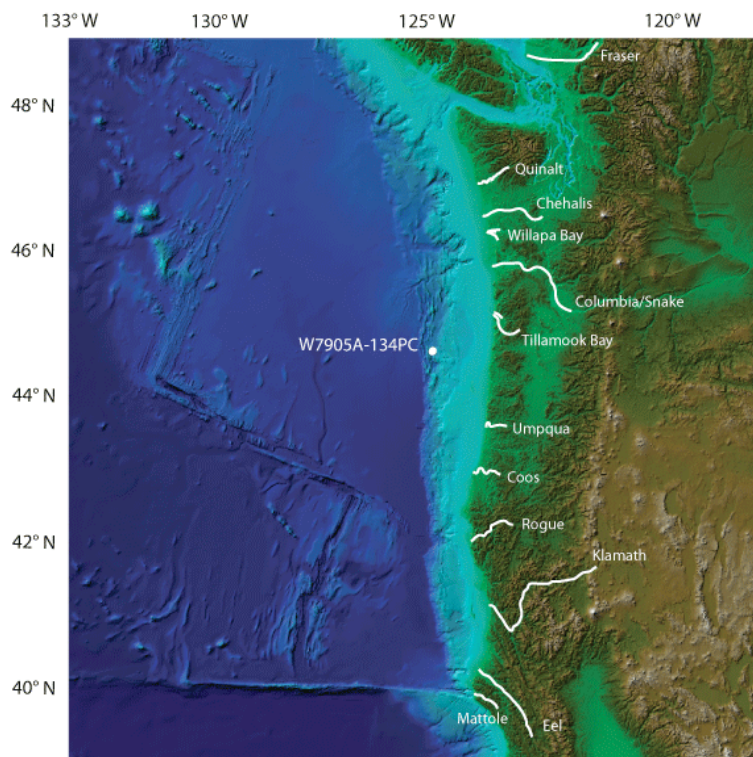


Figure 14:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of sediment core W7905A-114TW and  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $\epsilon_{\text{Nd}}$  of proximal river sediment sources. Note that  $\epsilon_{\text{Nd}}$  was not measured for this core, so it is depicted as a vertical bar. Grey vertical lines reflect the Ar/Ar plateau age of rivers whose  $\epsilon_{\text{Nd}}$  was not measured. The primary source of sediment to the site appears to be the Columbia River.



*Y6705-22PC*

Core Y6705-22PC is located offshore of southern Oregon. Given  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $\epsilon_{\text{Nd}}$  alone, it appears to be composed of entirely Sacramento and San Joaquin River sediments (see Figure 15). These rivers are located in central California and discharge into the San Francisco Bay. It seems highly unlikely, though possible, that sediments from these rivers travel from central California to Southern Oregon. Alternatively, the surface sediments at core Y6705-22PC could be comprised of a mixture of Rogue and Umpqua sediments, with some contribution by the Coos River. Another provenance technique would need to be employed in order to differentiate between these sources.

*Y7211-1GC*

The sediments found in the core top at this site, located offshore of the Coos River, have anomalously low  $\epsilon_{\text{Nd}}$  values (see Figure 16). This indicates sediments derived from very old portions of the granitic crust. The  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age would suggest that sediments at the site are composed of Rogue, Coos, and Umpqua River sediments, but the source terrains eroded by these rivers are not as old as the  $\epsilon_{\text{Nd}}$  values would suggest. The sources of error that could have caused this anomaly will be later discussed in detail.



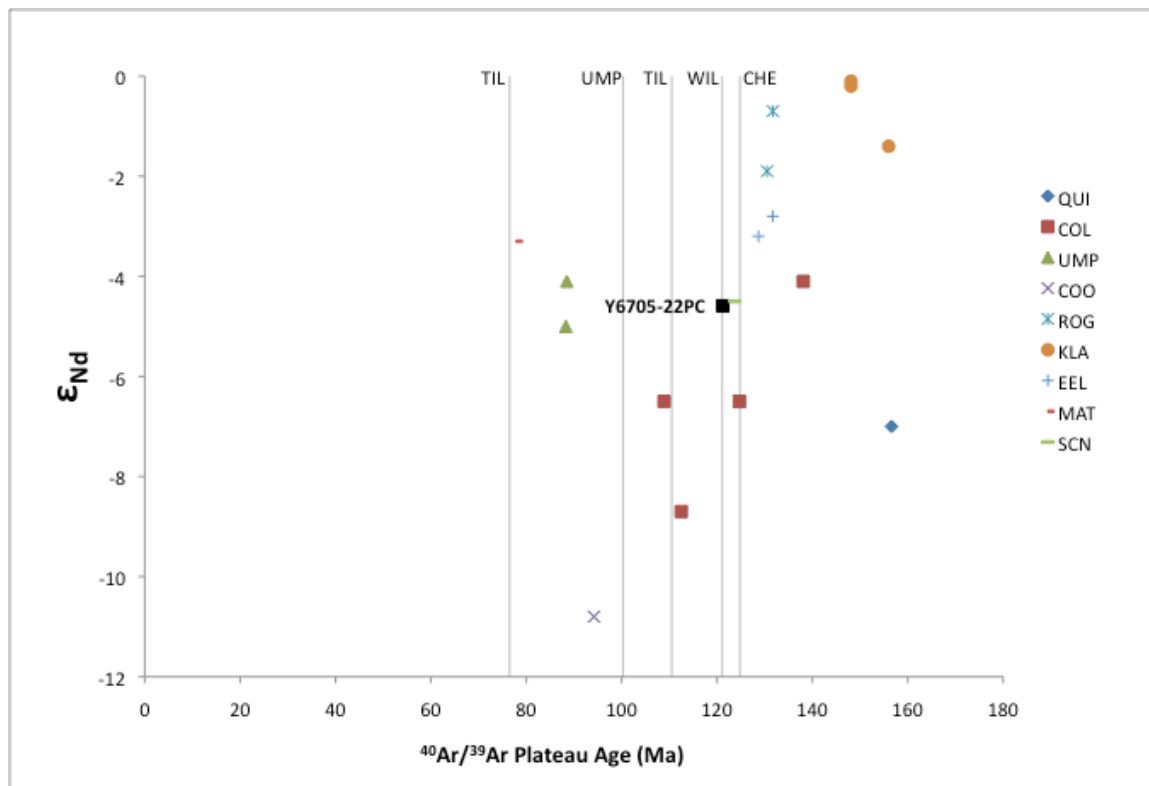
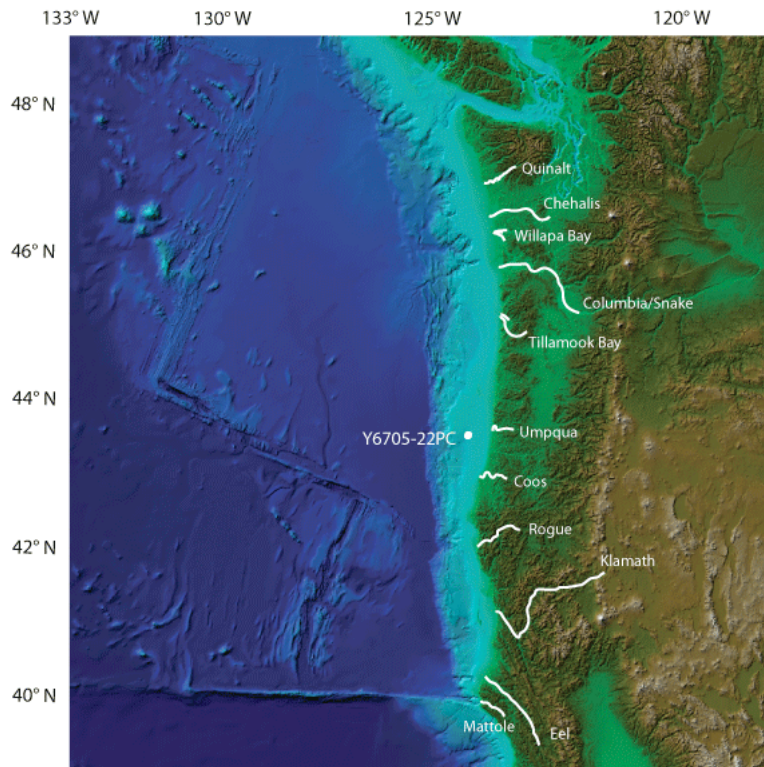


Figure 15:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core Y6705-22PC and proximal river sediment sources. Vertical lines represent the  $Ar/Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary river source of the sediments is unlikely to be the Sacramento River in central California (not pictured on the map). More likely, the sediments are composed of a mixture of Rogue, Umpqua, and Eel River sediments.



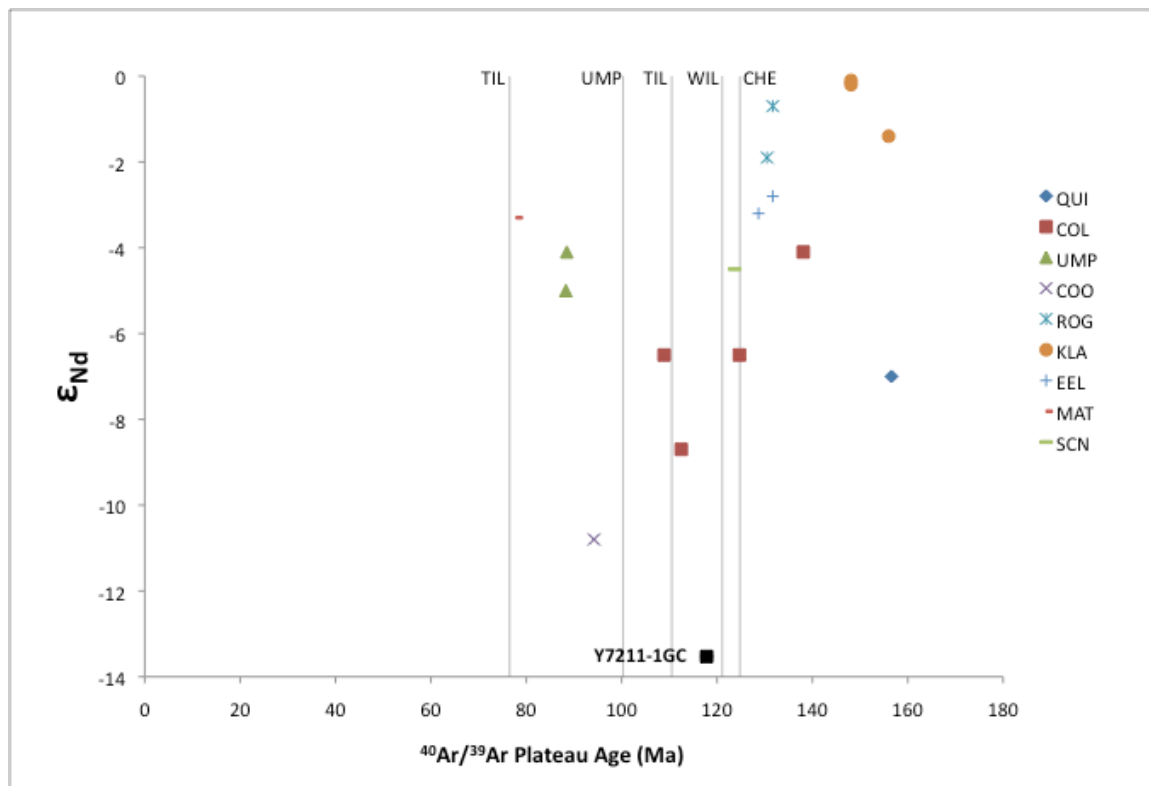
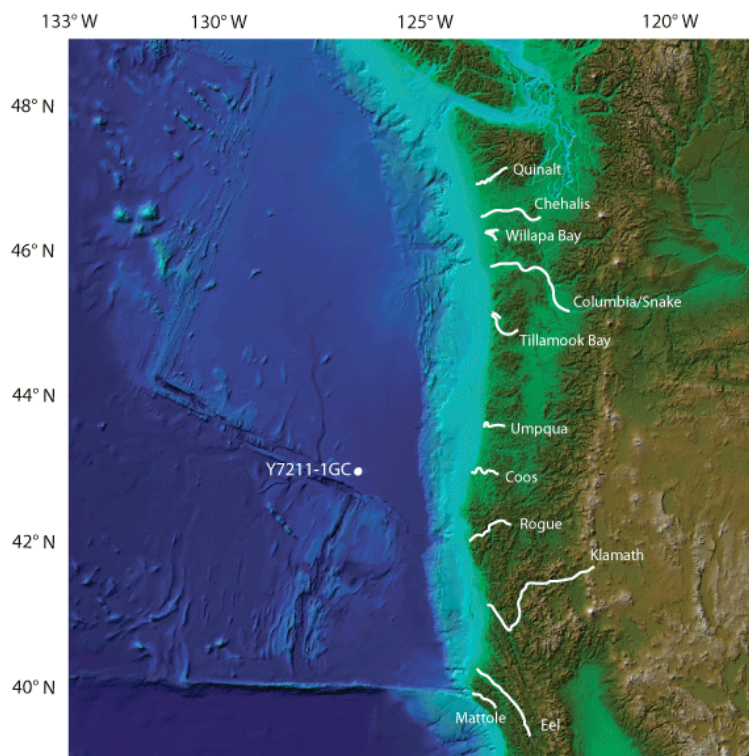


Figure 16:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core Y72-11-1GC and proximal river sediment sources. Vertical lines reflect the  $Ar/Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary sources of the sediments cannot be determined from modern Pacific Northwest river sediments.



*Y6604-11PC*

This core is located off the coast of southern Oregon. It is composed of Rogue River sediments, as well as some Umpqua river sediments (see Figure 17). The input of Coos River sediments is surprisingly limited given the proximal location of the river.

*Y6604-12PC*

This core is located off the coast of southern Oregon, just southeast of Y6604-11PC. It too is composed of primarily Rogue River sediments, but with little to no input from the Umpqua River (see Figure 18). The site appears to be receiving sediments from the Eel River. While the site is located well north of the Eel, the river has a very high sediment discharge, and it is possible that Eel River sediments could be transported as far northward as core site Y6604-12PC. Sediments found at the site are very similar to Eel River sediments in terms of both  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $\epsilon_{\text{Nd}}$  values.



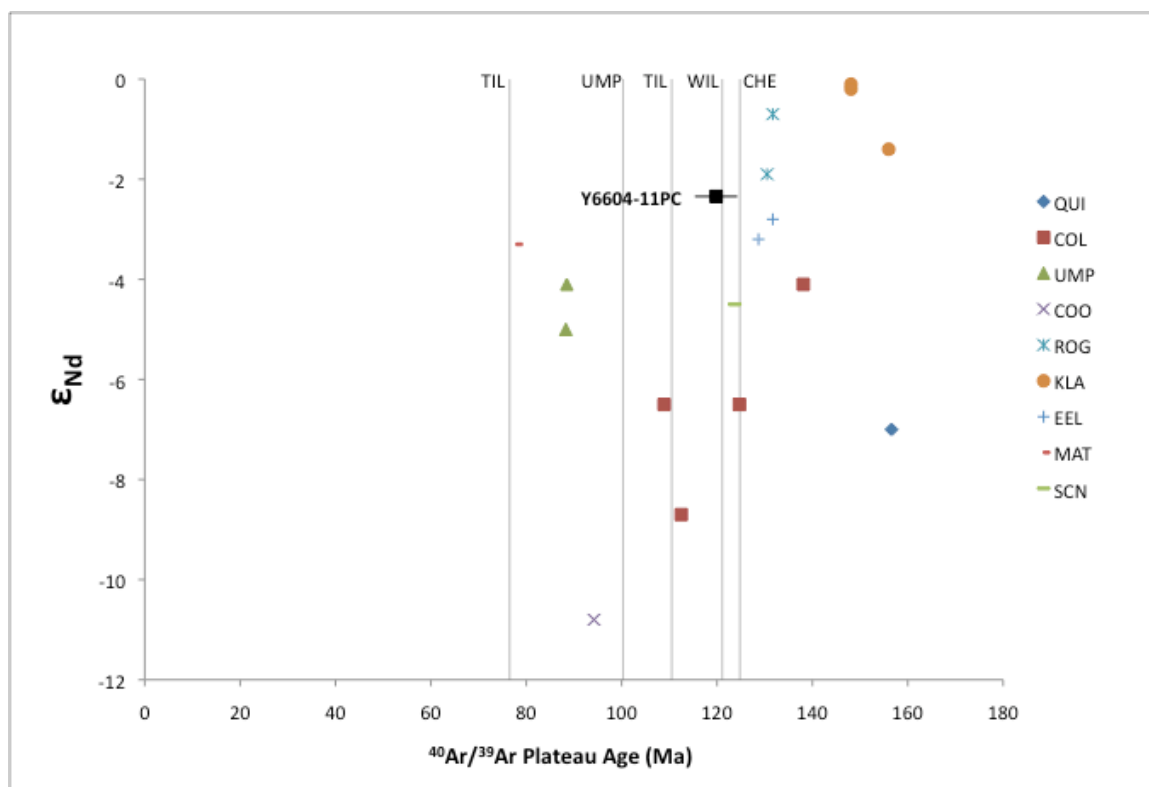
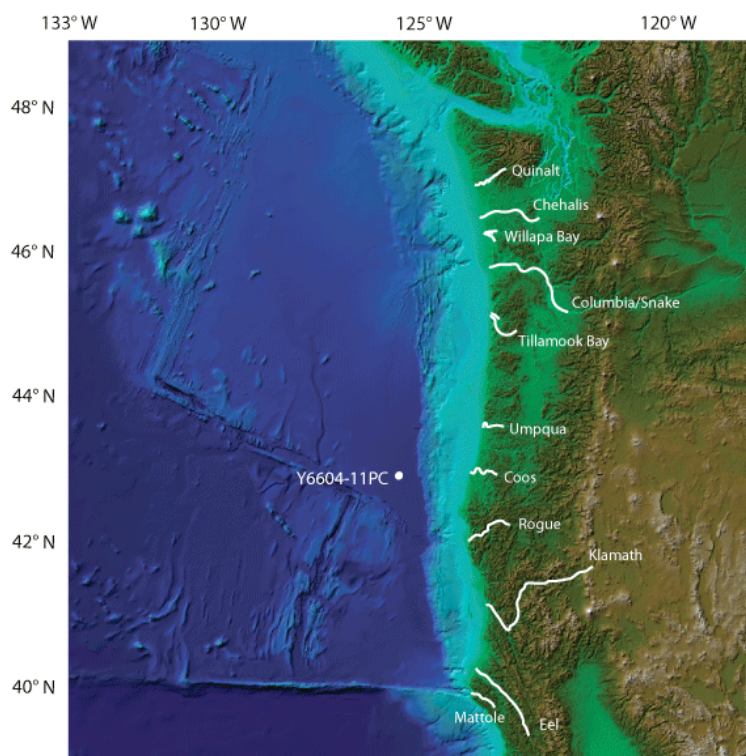


Figure 17:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age and  $\epsilon_{\text{Nd}}$  of sediment core Y6604-11PC and proximal river sediment sources. Vertical lines represent the  $\text{Ar}/\text{Ar}$  plateau age of rivers whose  $\epsilon_{\text{Nd}}$  was not measured. The primary river source of the sediments is the Rogue, with additional input from the Umpqua and surprisingly limited input from the Coos River.



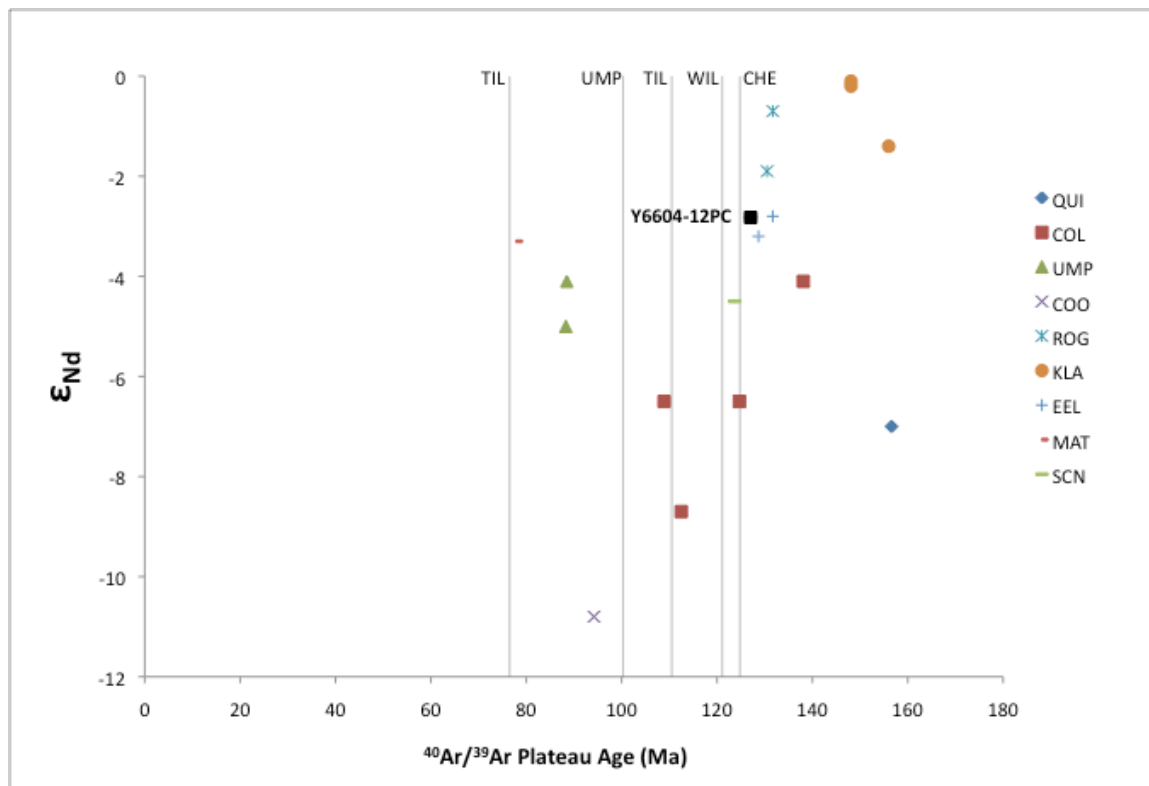
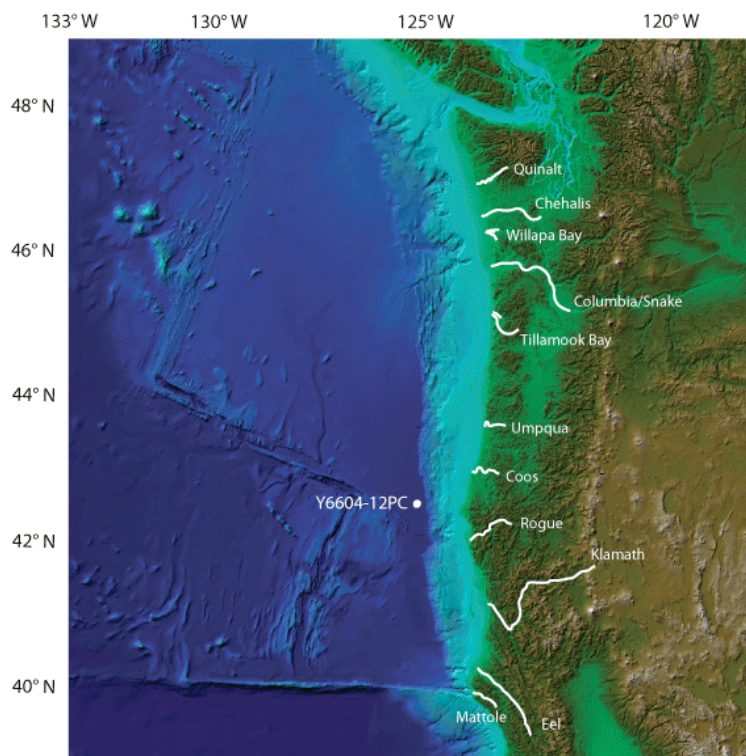


Figure 18:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core Y6604-12PC and proximal river sediment sources. Vertical lines reflect the  $^{40}Ar/^{39}Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary river sources of the sediments are the Eel and Rogue Rivers.



*Y-74-1-08MG*

Core Y-74-1-08MG is located off the coast of northern California, proximal to the Eel and Mattole Rivers (see Figure 19). Surface sediments at this site are composed of a mixture of Mattole, Sacramento, and San Joaquin Rivers. There is little to no contribution from Eel River sediments at this site.

*Y-73-10-100MG*

The core top at this location is of Pleistocene origin (2.58Ma-12ka), as indicated by the presence of the radiolaria species *Lamprocyrtis heteroporus*. Regardless, the provenance data from this site tells an interesting story, even if it will not be considered as part of the array of surface samples. The  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age is much younger than any of the modern source terrains in the Pacific Northwest (see Figure 20). There are several possible explanations for this. During the Pliocene, sedimentation rates were much higher off the coast of California than they are at present (Isaacs, 1980). At the Pleistocene/Pliocene transition, this sedimentation rate decreased. One hypothesis for the decrease in sedimentation is that all young material (recently eroded by glaciation) was removed from the California drainage basins, and rivers began to erode the older basement rock that is observed today in river sediments (Isaacs, 1980). At the time of sediment deposition at core Y-73-10-100, the river systems may have been eroding this younger material before it was depleted, resulting in the observed young  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age. To test this hypothesis, a future project could look for this young  $^{40}\text{Ar}/^{39}\text{Ar}$  signal in other cores at the Pleistocene/Holocene transition.

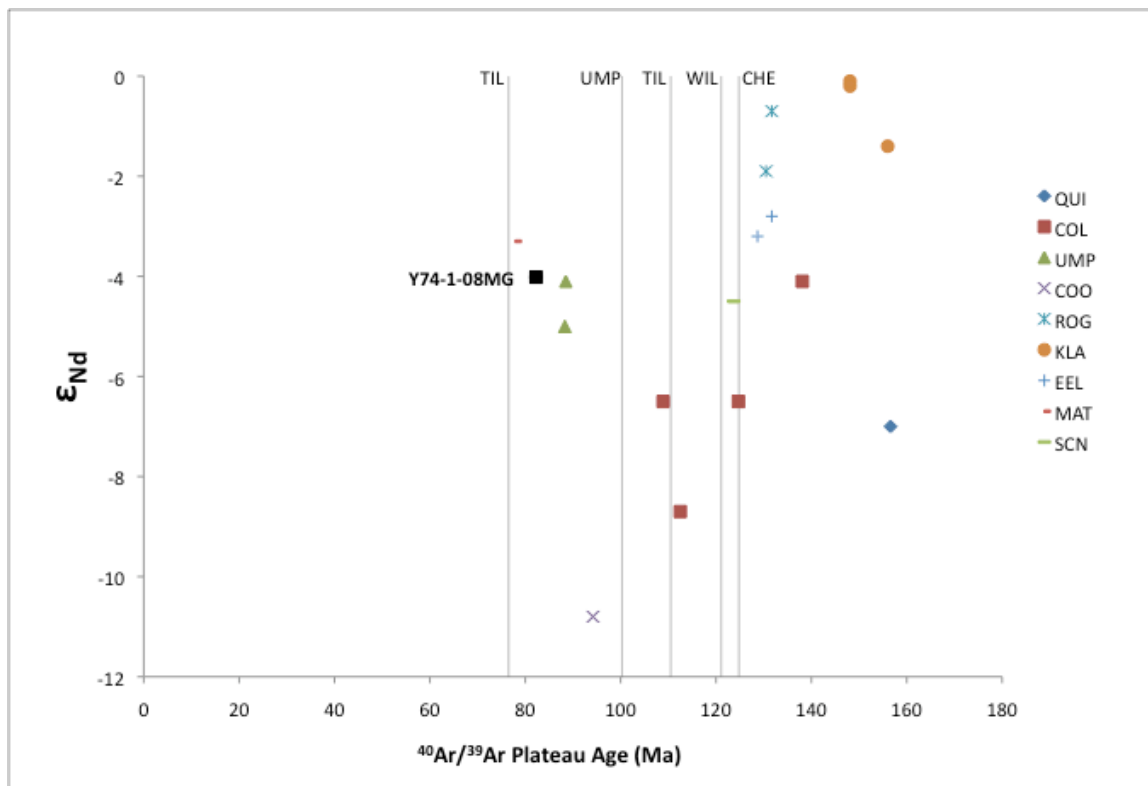
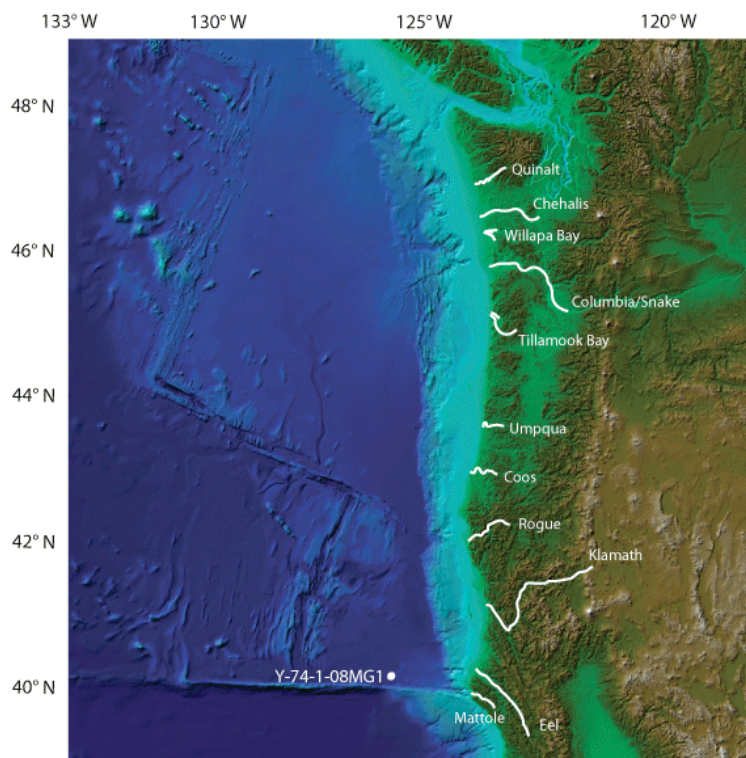


Figure 19:  $^{40}Ar/^{39}Ar$  plateau age and  $\epsilon_{Nd}$  of sediment core Y74-1-08MG and proximal river sediment sources. Vertical lines represent the  $^{40}Ar/^{39}Ar$  plateau age of rivers whose  $\epsilon_{Nd}$  was not measured. The primary river source of the sediments are the Mattole and Sacramento Rivers (not pictured on the map, located in central California), with surprisingly limited input from the Eel River.





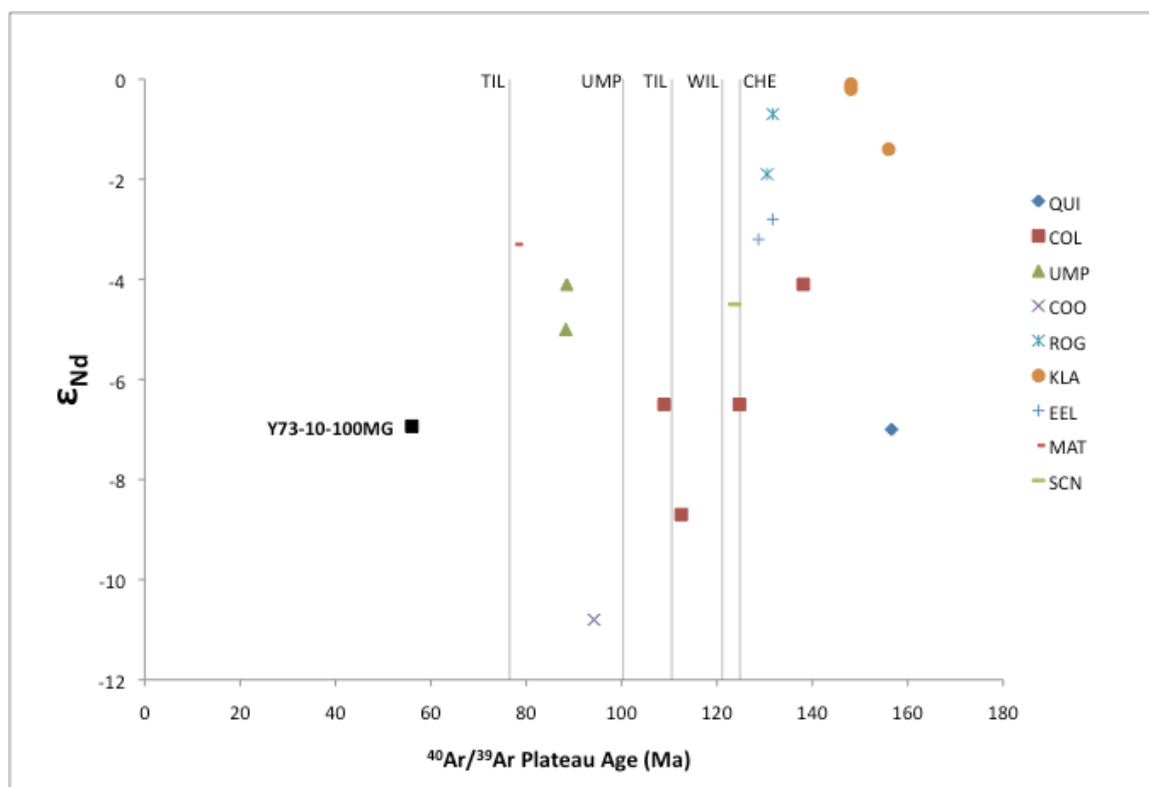
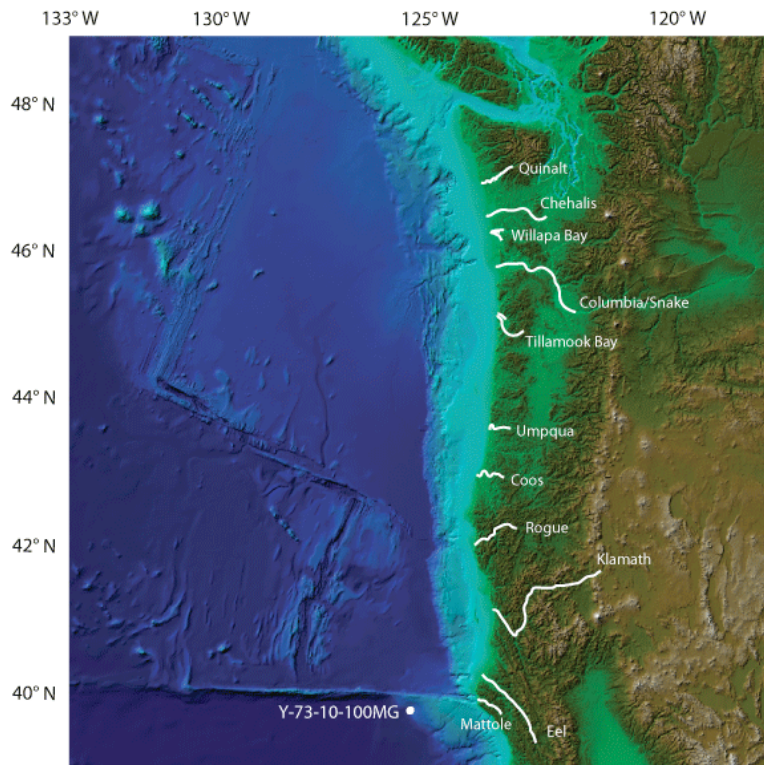


Figure 20:  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age and  $\epsilon_{\text{Nd}}$  of sediment core MV9907-20TC and proximal river sediment sources. Vertical lines represent the Ar/Ar plateau age of rivers whose  $\epsilon_{\text{Nd}}$  was not measured. Micropaleontology of the core showed that it is not composed of modern sediments, and was instead deposited during the Pleistocene.



## DISCUSSION

Overall, sediments found offshore reflect proximal river sources, with net northward transport of sediments prior to deposition. This is particularly seen in the case of Rogue, Eel, Coos, and Mattole Rivers (see Figure 21). At several core sites, net northward transport of sediments from nearby rivers means that samples taken just offshore of a given river may not contain material deposited by that river. This is seen at core top Y-74-1-08MG (which does not appear to contain Eel River sediments), and Y6604-11PC (which does not appear to contain Coos River sediments), and several other locations. In all instances, cores located farther to the north of the river do see sediment signals from that river but continental margin sites at the same latitude do not. This trend makes sense: in the NE Pacific, most sediments are deposited into the ocean by rivers during winter storms, when the northward flowing Davidson current (California counter-current) is strong.

There are several outliers to this trend. Core top MV9907-20TC is composed primarily of Columbia River sediments, although it is located well south of the mouth of the Columbia. The Columbia and Eel have the highest sediment discharge of rivers in the region (see Table 1). We would expect that the geographic extent of those sediment plumes is also large. Dams have reduced the modern Columbia River sediment load dramatically, by up to 50-75% (Sherwood et al., 1990; Syvitski et al., 2005). At times in the past, however, discharge (and thus the extent of the sediment plume in the ocean) was much higher and could have deposited sediments as far south as core MV9907-20TC. From 17-13ka, catastrophic glacial lake outburst floods (called the Missoula floods) transported Columbia River sediments far into the Pacific Ocean (Bunker, 1982).

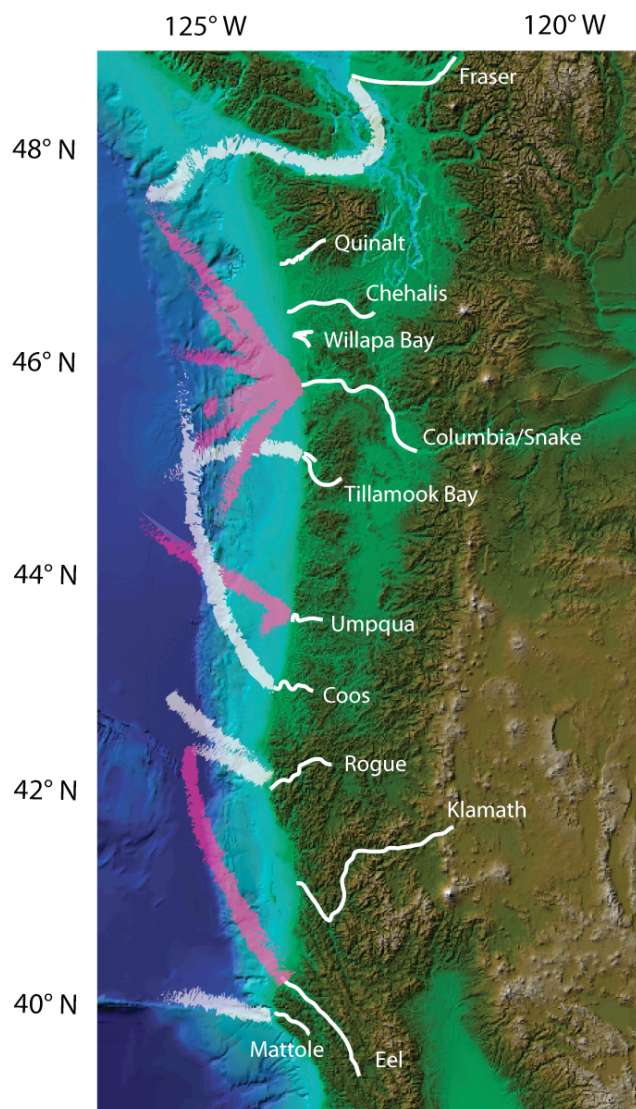


Figure 21: Hypothesized sediment transport from Pacific Northwest rivers to specific sample locations, based on  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  plateau and  $\epsilon_{\text{Nd}}$  of marine sediment samples. Note that lines do not represent overall sediment plumes from rivers, rather the general direction of sediment transport, as indicated by provenance data at individual core sites.

The sediments found at core top MV9907-20TC are not likely Missoula flood sediments; however, Cordilleran rocks from the continental interior dominate the sediment signature of the Missoula floods, so we would expect  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages and  $\epsilon_{\text{Nd}}$  values to trend

towards older ages and less radiogenic Nd isotopic values (Kulm et al., 1973; Duncan et al, 1970).

The provenance of sediments found at site Y7211-1GC cannot be explained using the techniques of this study. While the Ar/Ar plateau ages suggest that the sediment at the site comes from proximal rivers (the Rogue, Coos, and Umpqua), the  $\epsilon_{\text{Nd}}$  suggests a bedrock source from a very old portion of the granitic crust, like a craton. Less-radiogenic sediments would be expected of Missoula flood sediments, but the Ar/Ar plateau age does not suggest material this old. We remain unable to explain this  $\epsilon_{\text{Nd}}$  result. It is likely the product of experimental error, and should be re-analyzed

There are several major sources of error inherent in marine sediment geochemistry. The seafloor is a changing environment. Bioturbation, or the movement of marine sediments by organisms on the seafloor, can move sediments from one location to another. Turbidites, or large debris-flows on the sea floor, can dramatically alter the composition of sediments found at a site. Both bioturbation and turbidites can result in older sediments being deposited on top of younger sediments, mixing the paleoclimatic signals found in sediment cores. Micropaleontology was used in this study to confirm that the ‘modern’ sediments that were analyzed were not deposited during a glacial period, but there is little way to confirm that sediments were not deposited during a previous interglacial period. Sediment collection by gravity core or piston core can also re-work sediments, resulting in older sediments being collected as core-top samples. Additionally, experimental error in lab work may have resulted in erroneous data. The lab work that was performed as part of this project was all new to the author, and mistakes in experimental procedure undoubtedly occurred. Experimental error is likely responsible



for the anomalously low  $\epsilon_{Nd}$  values seen at cores Y7211-1GC and W7905A-114TW. In order to avoid these kind of experimental errors in the future, there should be duplicate runs of each sample. This kind of replicate sampling was beyond the scope of this project, however.

One consideration when dealing with terrestrial sediment material is anthropogenic disturbance. Humans have greatly changed rivers over the last 200 years, building dams and reservoirs. River transport of sediments has increased as erosion along banks has increased due to urbanization, deforestation, agricultural practices, and mining (Syvitski, 2005). Despite these huge impacts on the sediment transport of rivers, the annual flux into the ocean does not appear to have been greatly altered (Syvitski, 2005). The most altered rivers are able to trap increased sediment load in basins within the catchment, preventing these sediments from reaching the ocean. At this time, anthropogenic disturbance to sediment flux is not a significant factor in studies regarding the terrigenous sediment record.

## IMPLICATIONS AND FUTURE WORK

This project has established that the combined  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $\epsilon_{\text{Nd}}$  technique for determining provenance of marine sediments is viable and effective for use in the Pacific Northwest. The provenance of modern sediments deposited along the continental margin was determined, and the results are as expected (given current climate and ocean circulation). In order to address the questions posed regarding the fidelity by which margin sediments record the terrigenous sediment input of proximal rivers on glacial-interglacial timescales, a provenance record needs to be established over glacial-interglacial cycles at select core sites. This record should be established for distinct time intervals that are also being modeled by the RegCM2 climate model (Hostetler et al., 1999). If terrigenous sediment accumulation rates are also measured at each of these longer ‘record’ sites, the RegCM2’s output model results should be able to test the hypothesis that terrigenous sediment accumulation in the Pacific Northwest reflects variable continental rainfall and runoff. The results of model runs should be able to predict the timing and magnitude of sediment accumulation changes if this is the case.

There are three long cores within the Pacific NW array which could be used in future studies attempting to compile this provenance record. Cores EW9504-17PC, EW9504-13PC, and ODP Site 1019 should be sampled using a nested sampling strategy. These cores could provide complete, high-resolution paleoceanographic and pollen records spanning the last few glacial cycles of the NE Pacific (Pisias et al., 2006).

Once a record of terrigenous sediment provenance is established over glacial-interglacial cycles, it can then be compared to the marine pollen record. If it is found that changes in provenance occur simultaneously with changes in the marine pollen record, the future use of the pollen record should be re-evaluated. These results would signify that the marine pollen record is not a faithful reflection of proximal terrestrial vegetation, and is instead highly impacted by pollen transport pathways. In other words, a change in the pollen record signifies a change in ocean currents or river conditions instead of a change in vegetation on land.

Marine sediments along continental margins contain detailed records of both terrestrial and marine records, making them extremely valuable to climate studies. Despite the potential for holistic studies of the climate system by using marine sediment cores in this way, little research has attempted to couple the terrestrial and marine records (VanLaningham et al., 2006). The continuation of this project will add to this knowledge base as it examines how terrigenous sediments can be used to study climate.

## REFERENCES

- Bunker, R. C. 1982. Evidence of multiple late-Wisconsin floods from glacial Lake Missoula in Badger Coulee, Washington. *Quaternary Research* 18, 17-31.
- Brandon, M. T., Vance, J. A. 1992, Tectonic evolution of the Cenozoic Olympic subduction complex, Washington state, as deduced from fission track ages for detrital zircons: *American Journal of Science* 292, 565-636.
- Broecker, W.S., Peng T. H. 1982. Tracers in the Sea. Lamont-Doherty Geological Observatory.
- Duncan, J. R., Kulm, L. D., Griggs, G. B. 1970. Clay mineral composition of the Late Pleistocene and Holocene sediments of the Cascadia basin, Northeast Pacific Ocean. *Journal of Geology* 78, 213-221.
- Gardner, J., Dean, W.E., Dartnell, P. 1997. Biogenic sedimentation beneath the California Current System for the past 30kyr and its paleoceanographic significance. *Paleoceanography* 12, 207-225.
- Ghosh, D. 1995. Nd-Sr isotopic constraints on the interactions of the intermontane Superterrane with the western edge of North America in the southern Canadian Cordillera: *Can. Jour. Earth Sci.* 32, 1740-1758.
- Giorgi, F., Marinucci, M. Bates, G. 1993. Development of a second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer processes. *Monthly Weather Review* 121, 2794–2813.
- Hebbeln, D., Lamy, F., Mohtadi, M., Echtler, H., 2007. Tracing the impact of glacial-interglacial climate variability on erosion of the southern Andes. *Geology* 35, 131-134.
- Hemming, S. R., Broecker, W. S., Sharp, W. D., Bond G. C., Gwiazda, R. H., McManus, J. D., Klas, M., Hajdas, I., 1998. Provenance of Heinrich layers in core V28-82, northeastern Atlantic:  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of ice-rafted hornblende, Pb isotopes in feldspar grains, and Nd-Sr-Pb isotopes in the fine sediment fraction. *Earth and Planetary Science Letters* 164, 317-333.
- Heusser, L., Balsam, W.L., 1977. Pollen distribution in the Northeast Pacific Ocean. *Quaternary Research* 7, 45-62.
- Heusser, L., Lyle, M., Mix, A., 2000. Vegetation and climate of the northwest coast of North America during the last 500 ky. High resolution pollen evidence from the northern California Margin. In: Lyle, M., Koizumi, I., Richter, C. (Eds.), *Proceedings ODP167: College Station, TX (Ocean Drilling Program)*, pp. 217-226.

Hostetler, S., Bartlein, P. 1999. Simulation of the Potential responses of regional climate and surface processes in western North America to a canonical Heinrich event. *Monthly Weather Review* 121, 2794-2813.

Huyer, A., 1983. Coastal upwelling in the California Current System. *Progress in Oceanography* 12, 259-284.

Isaacs, C. 1980. Diagenesis in the Monterey formation examined laterally along the coast near Santa Barbara, California. PhD Dissertation, Stanford University.

Karlin, R., 1980. Sediment sources and clay mineral distributions off the Oregon Coast. *Journal of Sedimentary Petrology* 50, 543-560.

Kulm, L. D., Prince, R. A., Snavely, P.D., 1973. Site Survey of the northern Oregon continental margin and Astoria Fan. Init. Rep. Deep Sea Drill Proj., v. XVIII, no. Appendix I, Part A, 979-987.

Koppers, A.A.P., 2000. ArArCalc- software for  $^{40}\text{Ar}/^{39}\text{Ar}$  age calculations. *Computers and Geosciences* 28, 605-619.

McDougall, I., and Harrison, T. M., 1999, *Geochronology and thermochronology by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method*: New York, Oxford University Press, 269.

McLaughlin, R. J., Sliter, W. V., Fredriksen, N. O., Harbert, W. P., and McCulloch, D. S., 1994. Plate motions recorded in tectonostratigraphic terranes of the Franciscan Complex and evolution of the Mendocino Triple Junction, Northwestern California. *U.S. Geological Survey Bulletin*, 60.

Monger, J. W., Price, R. A., and Templeman-Kluit, D. J., 1982, Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera: *Geology* 10, 70-75.

Nigrini, C., Moore, T. C. Jr., 1978. A guide to modern radiolaria. Cushman Foundation for Foraminiferal Research, Special Publication No. 16.

Pisias, N. G., Mix A.C., Heusser, L., 2001. Millennial scale climate variability of the northeast Pacific ocean and northwest North America based on radiolaria and pollen. *Quaternary Science Reviews* 20, 1561-1576.

Pisias, N. G., Hostetler, S., Duncan, R.A., 2006. The Pacific Northwest ocean-land response to millennial scale climate change: an integration of model and geologic data sets. National Science Foundation Proposal.

Pisias, N.G., Duncan, R.A., 2008. Integration of models and geologic data to constrain joint marine-terrestrial responses to millennial scale climate change in the Pacific Northwest. National Science Foundation Proposal PD 98-1620.

Reneau, S. L., Dietrich, W. E., Dorn, R. I., Berger, C. R., Rubin M. 1986. Geomorphic and paleoclimatic implications of latest Pleistocene radiocarbon dates from colluvium-mantled hollows, California. *Geology* 14, 655-658.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., DePaolo, D.J., 1998. Intercalibration of standards, absolute ages, and uncertainties in  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. *Chemical Geology* 145, 117-152.

Roelofs, A. K., Pisias, N. G., 1986. Revised technique for preparing quantitative radiolarian slides from deep-sea sediments. *Micropaleontology* 32, 182-185.

Roy, M., Flierdt, T., Hemming, S., Goldstein, S. 2007.  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of hornblende grains and bulk Sm/Nd isotopes of circum-Antarctic glacio-marine sediments: Implications for sediment provenance in southern ocean. *Chemical Geology* 244, 507-519.

Sabin, A.L., Pisias, N.G., 1995. Sea surface temperature changes in the Northeastern Pacific Ocean during the past 20,000 years and their relationship to climate change in northwestern north America. *Quaternary Research* 46, 48-61.

Segar, D. 2007. Introduction to Ocean Sciences, 2<sup>nd</sup> ed. W. W. Norton & Company, Inc.

Sherwood, C. R., Jay, D. A., Harvey, R. B., Hamilton, P., and Simenstad, C. A., 1990, Historical changes in the Columbia River estuary. *Progress in Oceanography* 25, 299-352.

Stille, P., Shields, G., 1997. Radiogenic Isotope Geochemistry of Sedimentary and Aquatic Systems. Springer Berlin, 33-45.

Sverdrup, K., Duxbury, A.C., Duxbury, A.B. 2003. An Introduction to the World's Oceans, 7<sup>th</sup> ed. McGraw Hill.

Syvitski J.P.M., Vorosmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediments to the global coastal ocean. *Science* 308, 376-380.

Takahashi, K., 1997. Siliceous microplankton fluxes in the eastern subarctic pacific 1982-1986. *Journal of Oceanography* 53, 455-466.

VanLaningham, S., Duncan R.A., Pisias, N.G., 2006. Erosion by rivers and transport pathways in the ocean: a provenance tool using  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  incremental heating on fine-grained sediment. *Journal of Geophysical Research* 111 (F04014).

VanLaningham, S., 2007. The fluvial response to glacial-interglacial climate change in the Pacific Northwest. Ph.D. Thesis, Oregon State University.

VanLaningham, S., Duncan R.A., Pisias, N.G., 2008. Tracking fluvial response to climate change in the Pacific Northwest: a combined provenance approach using Ar and Nd isotopic systems on fine grained sediments. *Quaternary Science Reviews* 28, 495-517.

Walker, G. W., and MacLeod, N. S., 1991. Geologic Map of Oregon: U.S. Geological Survey, scale 1:500,000.

Walter, H. J. , Hegner, E., Diekmann, B., Kuhn, G., Rutgers Van Der Loeff, M. M., 2000. Provenance and transport of terrigenous sediment in the South Atlantic Ocean and their regions to glacial and interglacial cycles: Nd and Sr isotopic evidence. *Geochimica et Cosmochimica Acta* 64, 3813-3827.

Wheatcroft , R. A., Sommerfield, C. K. 2005. River sediment flux and shelf sediment accumulation rates on the Pacific Northwest margin. *Continental Shelf Research* 25, 311-332.