PROJECT SUMMARY

Overview:
The Columbia River flood basalts (CRB) are dominated by the Grande Ronde flows, which are an ending phase of northward volcanic propagation away from the Yellowstone hotspot track. Their large volume and basaltic andesite composition imply a large crustal magma chamber(s) and a reconstructed crust. Yet, the location of this crustal chamber is debated, with two leading hypotheses: motivated by seismic and uplift evidence for lithospheric delaminations, a spatial evolution hypothesis has a delamination-driven propagation of the magmatic source causing the propagation of eruptive centers; motivated by the pattern of CRB dikes and evolving magma chemistry, a temporal evolution hypothesis has a large chamber beneath the western Snake River Plain region, with propagation of eruptive centers fed by evolving dike patterns. We propose a seismic study of NE Oregon and environs to image the crust where the spatial evolution hypothesis predicts a large magma chamber; the crust in the area of the chamber predicted by the temporal evolution hypothesis is being studied by the IDOR seismic investigation. Specifically, our goals are: (1) to seek and image the hypothesized northern crustal chamber, and thereby address whether the major eruptions in this area at 16 Ma are due primarily to the foundering of the pluton root that caused Wallowa Mt uplift or whether the eruption originated to the south and is unrelated to the formation of the Wallowa Mts; (2) to image the top of the previously-imaged foundered lithosphere beneath NE Oregon and resolve its relationship to the crust; and (3) to understand the petrologic role of recently discovered lavas that are products of late-stage melting of eclogite, which may provide insight on the nature of the deep modified crust. More broadly, the goals are to understand the role of magmatism in lithospheric foundering, the role of lithospheric foundering on flood basalt magmatism, and processes of mass addition and loss in the crust and continental lithosphere.

Intellectual Merit:
Lithospheric foundering and flood basalt eruptions are two important processes that act at the base of lithosphere, and thus are remote and somewhat obscure. The Grande Ronde flood basalts, Wallowa pluton uplift and lithospheric foundering that is clearly related to these events, are an outstanding set of structures that provide insight into the causes and controlling properties of these bottom-side processes. Previously discussed mantle structures and uplift patterns lead to strong hypotheses, but the important role of the crust in the activity is very poorly understood. This greatly limits understanding of the underlying processes and their consequences, especially on crustal reconstruction.

Broader Impacts:
(1) We will train young scientists in integrative and collaborative science. Both PIs have good track records for the success of their students and postdocs. (2) A major effort will involve three undergraduate students logistically organized and largely funded through an REU and the Keck Geology Consortium. This will involve faculty and students from Whitman College (which is in our study area) and Oberlin College, in addition to Univ. of Oregon. Additional undergraduate participation at Caltech will be through their SURF (Summer Undergraduate Research Fellowship) program. Students will be involved with fieldwork and research. (3) The CRB eruptions dominate the landscape in most of eastern Oregon and Washington, and are of great natural interest to those living in the region. As with most of our other projects, our research team will give presentations in schools and community centers. We also work with the local media to engage the local population in the unique aspects of their geologic environment, and in the process of scientific investigation. (4) The causes and consequences of flood basalt events and lithospheric delaminations are important to fields as diverse as climate, landscape evolution, and continental creation. The CRB is the most recent and best-studied flood basalt event, and evidence is strong that two different styles of lithospheric foundering occurred recently in our study area. The uplift pattern created during Wallowa pluton uplift is the most distinctive and well-constrained example available.
Preamble. The primary objections to our previous submission were concerns about the geodynamic modeling of lithospheric foundering. We have removed this part of the proposal in response. The other concerns mentioned by the panel were:

• A need to better justify the regional portion of the seismic experiment. We now discuss: the significance of improved imaging in resolving volume, geometry, and amplitude of the inferred delaminated Farallon slab, especially for its relevance in testing the rollback-delamination hypothesis; and the greatly improved imaging that results from the use of 3-D ray tracing, along with the significant increase in station density.

• The hypotheses put forward were considered too narrow, with specific interest mentioned in the ideas about mantle flow driven by Juan de Fuca subduction, fragmentation, and rollback. Also, a desire was expressed to see testable ways to discriminate among hypotheses. These mantle flow processes are now introduced, the scale of our interests are better defined, and discriminatory tests are presented.

• The high cost of the project. The Oregon grad student who was to do geodynamic modeling has been removed from the proposal (saving $226K), PI Humphreys is reducing his requested Summer salary to 0.75 month/year (saving 19K; he will not reduce his effort), the Oregon postdoc is funded by Caltech (saving $31K), and undergraduate student support is now from the Keck Foundation (saving $37K).

• Absence of discussion on the PICASSO project (Humphreys was a participant, Bezada was his postdoc). The results of this project are briefly summarized here. Mediterranean slab rollback propagated west under the continental Alboran domain and beyond, drawing the resulting uplifted crust west (Bezada et al., 2013); similar forceful removal of continental lithosphere occurred along the margins of Africa and Iberia (Levander et al., 2014); Atlas uplift involved piecewise foundering of the mantle lithosphere (Bezada et al., 2014). The 3-D ray tracing improvement to tomography that will be applied in the proposed research, and its significant effects on refining the imaging, are presented in the 2013 paper. Through the PICASSO investigation we have expanded our understanding of delamination and foundering in environments where it is forcefully driven by the rollback subduction, its effects in nearby regions, and constrained the rollback-induced upper mantle flow field (with SKS splits; Miller et al., 2013) and partial melting field (Bezada et al., 2014). There are similarities with the eastern Oregon activity: both involve rollback (western Mediterranean with little melting and greater slab negative buoyancy) and dense-body foundering. In both cases, oceanic lithosphere tended to delaminate in a rollback style, whereas continental lithosphere foundering was more local and piecemeal. An additional study, unrelated to our current proposal, modeled the 650-km deep Granada earthquake. This earthquake included a clear, but very surprising, ~10-km-long slip-pulse rupture (Bezada & Humphreys, 2012).

Introduction

The Columbia River flood basalt (CRB) eruptions provide an opportunity to study how magmatic processes can make, restructure, and recycle continental crust and mantle. Also, because lithospheric foundering is clearly involved with this event, we have an opportunity to investigate the nature of magmatic-mechanical interactions and feedbacks that may often be important to major volcanic events. The CRB magma chemistry and the location of initial volcanism strongly implicate arrival of Yellowstone plume mantle at ~17 Ma (e.g., Wolff & Ramos, 2013). The sudden onset of volcanism suggests to many that plume ascent was stalled by interaction with the Juan de Fuca slab, with subsequent plume ascent being influenced, perhaps strongly, by mantle flow driven by the more dominant negative slab buoyancy (Faccenna et al., 2010; Liu & Stegman, 2012; James et al., 2012; Kincaid et al., 2013; Camp et al., 2015). Important interactions also occurred with the lithosphere, including flow excited by small-scale convection that probably entrained plume mantle. Each of these interactions may have had a significant effect on the spatial and temporal evolution of the CRB eruptions. Moreover, models that involve lithospheric delamination or a tear in the Juan de Fuca slab to allow plume passage (e.g., Liu & Stegman, 2012) require eclogite in the asthenosphere. The compositional consequences of near-plume eclogites have not been considered vis-à-vis Miocene alkaline lavas (e.g., Ferns et al., 2010; Ferns and McCloud, 2013; Nicolaysen et al., 2014) near the Wallowa seismic anomaly (Schmandt & Humphreys, 2011; Darold & Humphreys, 2013). The focus in our proposal is on the lithospheric interactions with the
plume, which appear to dominate the near-surface activity. In particular, distinctive surface uplift patterns (Hales et al., 2005) and imaged major mantle structures (Schmandt & Humphreys, 2011; Darold & Humphreys, 2013) lead us to think that once flood basalt magmatism began in southern Oregon, the progressively off-track and suddenly intense CRB volcanism was a consequence of plume-triggered lithospheric instabilities that include: (a) a north-propagating delamination of remnant Farallon lithosphere from the base of the northern half of eastern Oregon and (b) a subsequent foundering of a pre-existing pluton root beneath the NE corner of Oregon, where volcanism was most intense. While the evidence for these foundering events is strong, the nature and relation of CRB-related crustal activity to the mantle activity remains to be worked out. Of particular importance is resolving the location and size of the crustal magma chamber, which, surprisingly, is not known. Further, some consequences of delamination on magma genesis are not instantaneous, and the unexplored significance of olivine-bearing lavas that erupted contemporaneously with the Saddle Mountains Formation of the CRB is likely to be relevant. These coeval lavas are more magnesian (primary) and less silicic than any of the CRB, and they erupted on the margin of the Wallowa Mts near the area of the greatest concentration of CRB dikes. They therefore hold potential to address composition of melting sources in the vicinity of the Moho or uppermost mantle. To advance our understanding of the relation between magmatism and delamination, we will (1) investigate minor element abundances in olivine that are diagnostic for eclogite vs. peridotite source and (2) significantly improve imaging of two aspects of the inferred delaminated Farallon lithosphere: the transition where the inferred delaminated Farallon slab separates from North American lithosphere; and the shape, volume, and seismic amplitude of the delaminated lithosphere.

In this proposal, we first overview CRB volcanism in general, including a focus on the distribution and compositions of olivine basalt tholeiites and alkaline, olivine-bearing basanites previously grouped in the Powder River Volcanic Field (Ferns & McLaughry, 2013). First introduce the background information needed to understand the CRB volcanic event. The most important elements of this section are: the geological and geochemical evidence for the presence of a garnet-rich (dense) restite beneath the Wallowa pluton and the presence of Farallon slab at the base of eastern Oregon prior to the CRB event; and the seismic evidence that the major high-velocity structure beneath NE Oregon, the Wallowa mantle anomaly, (Fig. 1e-f) is the Farallon slab that foundered from the base of Oregon. We then describe a model for the origin of the Wallowa anomaly and the CRB volcanic event (Fig. 3). This is followed by our primary hypotheses, which relate the mantle processes to the crustal processes and the volcanism.

**Proposed Study Area**

In this section we present evidence for two interrelated foundering events in NE Oregon of different style: (1) rollback delamination of Farallon slab and (2) vertical foundering of a pluton-root. Each event expressed strong and different interactions with the flood basalt magmatism. Geologic observations provide important constraints on the conditions that preceded the flood basalt eruptions.

**Chronology of pre-delamination events**

• The area involved was a forearc to the Idaho Batholith ~50-150 Ma (Burchfiel et al., 1992; Giorgio, 2005), implying that there was little, if any, continental lithosphere between the subducting slab and the continental crust.

• Western U.S. was volcanically quiet during the Laramide orogeny. The cause of Laramide thrust faulting and volcanic quiescence is thought to be flat subduction of the Farallon slab against the base of North America (e.g., Coney & Reynolds, 1977).

At the latitude of our study, three things occurred at ~53 Ma:

• North of central Oregon, accretion of Farallon plate to the Pacific Northwest caused subduction to jump west to its present location (e.g., Wells et al., 2014).

• Normal-dip subduction was established beneath the accreted Farallon plate while flat-slab subduction continued to the south, creating an east-trending slab tear across central Oregon (Humphreys, 2009).

• Subsequent piecewise foundering of the flat slab is characterized by the ignimbrite flareup: where flat
slab remained there was no volcanism, and volcanism was vigorous where slab foundered (Armstrong & Ward, 1991; Humphreys, 1995, 2009). The ignimbrite flareup began ~53 Ma in Idaho, as Farallon slab foundered there; this foundered slab remains dangling beneath the region (seen in Schmandt & Humphreys, 2011). An absence of pre-CRB volcanism in NE Oregon and SE Washington following the Laramide orogeny seems to imply that Farallon slab was left at the base of this pre-accretion forearc (Darold & Humphreys, 2013).

Seismically imaged delaminated Farallon lithosphere. A major high-velocity upper-mantle structure, circular in map view, extends to a depth of ~350 km (Fig. 1e) directly below a pronounced topographic bullseye (Figs. 1 & 2e). Its large volume and seismic amplitude are too great to be anything but recently foundered oceanic lithosphere, and it resides in the space previously occupied by subducting Farallon lithosphere. Furthermore, it hangs below NE Oregon where pre-CRB magmatic quiescence suggests that the flat Farallon lithosphere remained in contact with North America. The sudden transition to CRB magmatism at 16.5 Ma suggests slab removal at this time (Darold & Humphreys, 2013). The slab can be followed up-dip and to the north where it flattens beneath SE Washington crust (Fig. 1e; seen more completely in Gao et al., 2011). It also can be followed up-dip and to the east where it joins with the large fragment of Farallon slab (Darold & Humphreys, 2013) that is thought to have delaminated at ~53 Ma (dotted line in Fig. 1f, Schmandt & Humphreys, 2011).

Flood basalt activity in the proposed study area. In our study area, post-Laramide volcanism began ~16.8 Ma (Fig. 2a; timing of Wolff & Ramos, 2013, after Jarboe et al., 2008, 2010) with the emergence of Yellowstone hotspot volcanism beneath the continental interior. The inferred relation between volcanism and the two delaminations is illustrated with the model shown in Fig. 3. The flood basalt eruptions began with the relatively small Steens flows (~15% of the total flood basalt volume of ~206,000 km³; Reidel et al., 2013). This activity occurred near the Oregon-Nevada border, near where simple back-projection of the Yellowstone hotspot track would predict. These basalts have a plume chemical signature that is similar to that of Yellowstone, but they also acquired chemical components of MORB asthenosphere (Fig. 4a; Wolff & Ramos, 2013; Carlson, 1984; Camp & Hanan, 2008) and North America mantle lithosphere (Carlson, 1984; Ramos et al., 2013).

Flood basalt volcanism propagated rapidly northward, starting the Imnaha eruptions ~100 kyr after the initial Steens eruptions (Fig. 2a-b; ~5% of the total volume). These lavas appear to be derived directly from the Yellowstone plume without significant amounts of assimilation (Wolff & Ramos, 2013; Fig. 4a). Volcanism reached NE Oregon beginning ~300 kyr after the initial Steens eruptions with the Grande Ronde flows (Fig. 2a-b). Volcanic production intensified greatly with this eruption, comprising ~72% of the total flood basalt volume. These lavas also have a clear plume component, but unlike the Steens, Imnaha, and other flood basalts worldwide, they are basaltic andesites (Fig. 4b), which cannot be derived from melting mantle. The two suggested explanations are: (1) a rapid (Ramos et al., 2005) large-volume assimilation of lower crust (Wolff & Ramos, 2013) by mantle-derived basalt or (2) a direct melting of a basalt-like source rock in the mantle (Takahahashi et al., 1998; Camp & Hanan, 2008). Grande Ronde lavas also have a component of Archean crust, which must have been acquired from Archean crystalline basement, which is exposed in Idaho (Figs. 2b & 4a). (During the time of Grande Ronde eruptions, an additional basaltic pulse erupted from the Monument dikes ~200 km to the west [Fig. 2b], comprising ~1% of the total flood basalt volume.)

The region’s major granitic pluton (the Wallowa pluton) rose 2 km above the surrounding country sometime after initial Imnaha volcanism, as evidenced by Imnaha lavas that cap this uplift. The 2-km uplift of the pluton (and essentially only the pluton; Fig. 1d) indicates a foundering (Hales et al., 2005) of a dense garnet-rich (O’Driscoll, 2007, from strong rare earth depletion trends) pluton root during the CRB eruptions. An approximate estimate of pluton restite thickness is found by assuming densities of 3350, 3000, 3300, and 2600 kg/m³ for, respectively, the restite, basalt, mantle, and granite pluton. Two km of isostatic uplift implies the replacement of 15 km of crustal restite with basalt. The restite loss would have...
vacated a large volume of lower crust that reasonably would become a large magma chamber. The amount of post-CRB uplift and the present-day topography of the bullseye are the same across the entire topographic bullseye (Figs. 1b,d; Hales et al., 2005), suggesting a related origin, and clearly indicating a major restructuring of the crust or upper mantle centered on the site of inferred pluton-root foundering. We have considered two possible origins for the sudden amplification of magmatic production (i.e., the Grande Ronde eruptions) in the vicinity of the inferred pluton-root foundering. One possibility is the forced overturn of Yellowstone plume mantle in the circular region around the sinking pluton root (Hales et al., 2005) in a manner similar to that used to explain the Siberian Traps flood basalts (Elkins-Tanton & Hager, 2000). However, if the upper mantle Wallowa anomaly were present at 16 Ma near its current location, this would have obstructed the form of mantle flow required in this model. An alternative possibility is the magmatic filling of the restite void and nearly contemporaneous assimilation of the lower or middle crust below the topographic bullseye. This option is bolstered by the need for large volumes of crustal assimilation with a contribution from Archean North America crust for the Grande Ronde lavas. Wolff & Ramos (2013) suggest the melting of an amphibolitic lower crust for these reasons (albeit in a more southerly location); Anita Grunder has informally suggested a metapeletic middle crust. Either of these cases would suggest that much or all of the topographic bullseye is underlain by a large, nearly circular magma chamber.

Then, only ~800 kyr (Wolff & Ramos, 2013) after the Steens eruptions began, volcanism quickly waned (Baksi, 2013, suggests ~600 kyr; Barry et al., 2013, suggest ~1200 kyr). The last ~7% of the total erupted volume occurred ~16.0-6.0 Ma, with most of this in the first 1 m.y. The youngest identified CRB formation is the Saddle Mountains Basalt, whose 10 members erupted from ~14.6 to 6 Ma (Barry et al., 2013). These basalts originated largely north and east of the Wallowa anomaly (Tolan et al., 2009). They also are the most compositionally diverse CRB group, and they experienced significant compositional modification in the crust. In contrast, 13.8 Ma olivine basalts of the Powder River Volcanic Field (Bailey, 1990) (or La Grande-Owyhee eruptive axis [Ferns & McClauhry, 2013]) are more primary than most of the CRB; preliminary data suggests these lavas resulted from high degree melts of mantle peridotite (Nicolaysen et al., 2014). Approximately 3 million years later, small volumes of highly sodic, olivine-bearing basanite erupted in the same area, between the present-day La Grande pull-apart graben and the Cretaceous plutons of the Wallowa batholith (Johnson et al., 1997; Zák et al., 2012). These basanites contain rare, angular small (<5 cm dia.) xenoliths of trondjhemite interpreted as poorly assimilated crust (Nicolaysen, unpublished data). Because of their high Fe, Ti, and Cr contents, the high densities of these small volume lavas may have prevented their eruption unless lithospheric thinning had already occurred.

**Hypotheses.** Our fundamental hypothesis is that the northward propagation and amplification of magmatism is a consequence of a rollback-style delamination of Farallon slab and a companion founder of plutonic restite, which we attribute, respectively, to the imaged mantle structure (Fig. 1e) and the Wallowa Mt uplift (Fig. 1b & d). An alternative hypothesis is that deeper mantle flow, driven by slab subduction and sinking, disrupted and complicated plume ascent to produce the anomalous magmatic observations. Both hypotheses are probable and not exclusive of one another. We focus on the lithosphere instability hypothesis for the northward propagation and amplification of magmatism because it is well supported by observations and holds the potential to be further developed through imaging, geochemical studies, studies of surface deformation, and geodynamic modeling.

Our general goals are to understand the processes that controlled and organized foundering and flood basalt magmatism, and the consequences of this coupled event on recycling and restructuring the continental crust and mantle lithosphere. Our investigation will focus on the lithospheric processes and scale, where our specific goal is to relate the mantle processes to the observed eruptive history by addressing what happened within the crust. Knowledge about the mantle structure (and its inferred history of development) is relatively good, as it is about the history of surface eruptions; it is in the crust, where the Grande Ronde assimilated large volumes of crust (e.g., Wolff & Ramos, 2013), that knowledge is too incomplete to understand the relations between the two, about what organized this
event, and about the consequences on reconstruction of the crust and mantle lithosphere. Within this context, there are two end-member hypotheses for the relationship of these delaminations to the CRB:

1. **Spatial Evolution Hypothesis**

In this hypothesis, the assumed delamination plays a dominant role. Magma chemistry evolves as delamination rollback draws Yellowstone plume north across eastern Oregon, encountering varying compositions and conditions, and culminating with the pluton-root foundering that excites rapid production of the Grande Ronde lavas ([Fig. 3; Darold & Humphreys, 2013; Camp & Hanna, 2008](#)). The Grande Ronde basaltic andesite composition may have contributions from melting one or more of three possible sources: (1) the Farallon oceanic crust, (2) lower or middle North American crust within the area of the bullseye, and (3) perhaps the foundered pluton root itself. These options involve rock units directly beneath our proposed array.

2. **Temporal Evolution Hypothesis**

This hypothesis is built around the radial pattern of dikes and faults created during the CRB eruptions ([Fig. 2b](#)). It is presented by Wolff & Ramos (2013) and Camp & Ross (2004). In this hypothesis, the CRB magmas occupy a large central magma chamber in east-central Oregon (yellow dashed oval in [Fig. 2b](#)) within which they evolve to create the distinctive Steens, Imnaha, and Grande Ronde magma types. Each magma type then propagates through dikes to the site of their respective eruptions in the southern, central, and northern parts of eastern Oregon. Magmatic evolution culminates with the assimilation of lower crust to produce the Grande Ronde basaltic andesites.

Minor weaknesses can be suggested for each of these hypotheses, and there are other models similar to those we chose as representative; the selected hypotheses give a sense of the variations that have been considered. Each of our hypotheses explains many of the observations on the CRB, and each incorporates a Yellowstone plume and an evolution in CRB magma chemistry that involves evolving compositions and amounts of lower crustal assimilation. However, each hypothesis also has significant incompleteness: the temporal evolution hypothesis does not address the imaged slab or the bullseye uplift pattern, and the spatial evolution hypothesis does not address the radiating dike pattern or the prominence of the western Snake River Plain. Most important to our proposal, these two classes of hypothesis are fundamentally different with respect to the processes by which the crust and upper mantle are modified, the causes and structural consequences of the magmatism, and (especially) the location of a large lower-crustal magma chamber and modification to the crust and underlying mantle. With respect to our two evolution hypotheses, we can frame our research plan with the question: Did delamination dominate (the spatial evolution hypothesis), with the plume drawn north in its wake, or did plume arrival dominate (the temporal evolution hypothesis) with delamination being relatively inconsequential?

* A simple hypothesis test statement. A significant magma body beneath the area of the foundered pluton root or topographic bullseye is absent in the temporal evolution hypothesis (which has upper crustal dikes transporting magma to NE Oregon from a more southerly magma chamber); its presence would falsify this hypothesis. Alternatively, an absence of evidence for large-scale magma production beneath the bullseye region in conjunction with the presence of a large magma chamber beneath east-central Oregon (at the center of the radiating dike pattern and west of the western Snake River Plain) would falsify the spatial evolution hypothesis. Our main seismic targets are the Wallowa-area crustal structure and its structural relation to the Wallowa mantle anomaly. The purpose is to resolve the physical relations that allow us to incorporate the crust into a CRB event that integrates activity from the mantle to the surface.

**Proposed Research**

We propose a seismic and a petrologic study, each designed to provide constraints on the nature of the Wallowa-area magma chamber, and each building off of our recent work ([Hales et al., 2005; Darold & Humphreys, 2013; Nicolaysen et al., 2014](#)). Our seismic study is based primarily on receiver function and
tomographic imaging, and our proposed array will optimize receiver function imaging across the region where we expect to find a major magma chamber. The petrologic study will improve understanding of the Grande Ronde source rocks and, especially, the late-stage magmas that indicate an eclogitic source.

**Seismic Studies**

Practically speaking, we can divide the data relevant to our seismic study into three categories: (1) those collected by the ID-OR investigation, discussed in the next paragraph; (2) those acquired by our proposed high-density line array, which is designed to image structure beneath the line to depths of ~80 km with high resolution; and (3) those acquired by the regional set of seismometers (including the line array and the ID-OR broadband array), which will be used to image a much larger volume of Earth.

The hypothesized western Snake River Plain magma chamber is being studied by seismologists Ray Russo and John Hole as part of their ID-OR investigation (*Deformation and Magmatic Modification of a Steep Continental Margin, Western Idaho – Eastern Oregon*). Their deployment collected broadband data that increased sampling density in the region of the western Snake River Plain by a factor of ~8, and also collected active-source seismic data along a line directly over the hypothesized magma chamber (*Fig. 5*). This study should resolve the size and seismic character of any significant magma chamber in this region.

With our studies, the emphasis is on the proposed line array; the regional imaging, discussed below, is considered of secondary importance.

**Seismic line array.** Our proposed seismic experiment is a 1.5-year deployment of 40 Guralp 3T (120 sec) seismometers deployed in a linear array of 4-km spacing and an embedded 2-week deployment of 200 high-frequency seismometers with a 100-m spacing (*Fig. 5*). Rather than distributing the stations over an area, this deployment geometry is chosen to maximize resolution along a critical transect that trends north from the central Wallowa Mts, across a topographic bullseye, and onto apparently undisturbed North American lithosphere. This line-array strategy has proven useful in Cascadia (*Li & Nábělek, 1999; Bostock et al., 2001*), Mexico (*Pérez-Campos et al., 2008*), Peru (*Phillips et al., 2012; Dougherty & Clayton, 2015*) and elsewhere. This geometry also is the only one possible in the vicinity of the Wallowa Mts because the region is a wilderness area, where deployment is forbidden. Our line follows the only non-wilderness swath along an access road into the center of the mountains.

With respect to our proposed seismic array, there are three important conclusions, drawn from the above discussion, that guide our deployment strategy: (1) *Wallowa pluton uplift of 2-km requires the foundering of a dense root 10-20 km thick.* The volume vacated by the Wallowa pluton root would have become a large magma chamber. (2) *The bullseye pattern of post-CRB crustal warping requires significant crustal modification,* perhaps involving a mid- to lower-crustal magma chamber beneath this wider area as well. (3) *The high-velocity upper mantle Wallowa anomaly is probably Farallon oceanic lithosphere that delaminated, starting in the south and rolling back to the north, leaving Farallon slab in contact with the base of SE Washington.* The two main targets are:

• the large crustal magma chamber beneath the Wallowa uplift and possibly beneath the entire topographic bullseye (*Figs. 1b & 2b,c*). The goal is to image the interfaces bounding this chamber, to follow the structures defining the magma chamber to their northern terminations, and to estimate the crustal seismic velocities.

• the upper portion of the mantle Wallowa anomaly, where the presumed Farallon lithosphere transitions from being in contact with SE Washington lithosphere to where it dangles beneath NE Oregon (*Fig. 1e*). A stringent test of our delamination hypothesis would be an image of oceanic crust under SE Washington that becomes absent on the dangling slab (where it would have melted). A related structural target is the vertical impedance structure of the continental Moho across the transition from a tectonic Moho (a former subduction interface, below SE Washington) to a magmatically constructed Moho beneath NE Oregon.

Previous seismic investigations provide information that is encouraging and suggestive of the crustal
structure in this region. A common-conversion-point stack of S-to-P receiver functions (Hopper et al., 2014) images a clear positive (slow above fast) mid- or upper-crustal discontinuity (Fig. 6b) that is confined to the region of the bullseye and suggestive of a large magma chamber. Also imaged is a locally depressed Moho near the Washington-Oregon border (shown in Fig. 1c, from Gao et al., 2011). This structure is interesting but difficult to interpret meaningfully. The collection of P-to-S receiver functions to single stations (Fig. 6a) provides a more detailed look. A characteristic of the Wallowa-area stations (W18 and W08) is a negative (fast above slow) arrival at ~2-3 seconds after the direct P arrival (at t = 0), indicated with blue arrows and dashed lines.

The bottom panel of Fig. 6c shows a N-S P-to-S receiver function profile. Crustal thickness variation is clear, as is the presence of structure internal to the crust. This structure motivates the synthetic test of the crustal magma chamber shown in the top panels of Fig. 6c. Results indicate that a structure similar to our target structure would be detected, but that the imaging quality needed for interpretation requires a higher-density station spacing such as we propose. With this station spacing, we will be able to use wavefield methods to image the scattered waves such as Kirchhoff-style migration (Bostock et al., 2001) and reverse-time imaging (Shang et al., 2012). We have learned from our experience in Peru that using different scattered phases can be important for constraining various aspects of the image (see Fig. 7), and we will incorporate this analysis into our images. We also plan to enhance the images with the use of correlations between earthquakes (Sanchis & Hansen, 2011) and by incorporating high-resolution ambient-noise tomographic imaging beneath the line array.

High-density array. We propose to deploy a 20-km-long 200-station high-density array for one month, using instruments provided by NodalSeismic (see NodalSeismic letter). The site we have chosen is within the topographic bullseye in the region where the Moho is depressed and the presumed Farallon lithosphere is separating from North America. These instruments will be easy to deploy in this area, and we are interested to “see what we get” as a possible guide to how this type of array can be applied to traditional deployments. We have had success with this type of instrumentation and station density for determining shallow structure with surface waves (Lin et al., 2013) and deeper structure with teleseismic waves (Schmandt & Clayton, 2013). In both of these studies, we were able to use waveform data to less than 1 Hz, despite the fact that the sensor starts to roll off at 10 Hz. We will also explore other imaging options. For instance, Fig. 8 shows clear arrivals in the autocorrelation of signals from a tight sensor cluster. These arrivals are probably reverberations of locally generated high-frequency ambient noise.

Because of a quirk in how the University of Oregon calculates overhead, the rental of the NodalSeismic instruments will be practically free. The rental cost is $57K. However, this budget item results in sufficient funds being spent off campus to qualify in the off-campus overhead rate of 26%, and this applies to the 3-year entire budget. The result is an overall cost reduction of $58K.

Regional broadband array. There are several hundred preexisting broadband stations in the Pacific Northwest, including ~300 sites within a 300 km radius of the mantle Wallowa anomaly. We will apply a broad suite of standard passive-source seismology techniques: teleseismic body wave and surface wave tomography, receiver function analysis, and SKS splitting analysis. The SKS splitting and regional receiver function studies are included because the data will be available, results probably will be useful, and they provide straightforward projects for undergraduate students using code that is well developed and tested. The value of these results is not known prior to analysis, but our experience is that they will be useful. For instance, receiver functions may resolve the lower-crustal boundary between the accreted Blue Mts terrane and Precambrian North America (i.e., the “Sr 0.706” line), and SKS splitting results may enable resolution of upper mantle fast-axis dip, which appears to be steep in this area (Long et al., 2009).

The primary regional project will be surface-wave and body-wave tomography, with the two main targets being the crust in and around the region of the possible Wallowa-area magma chamber and the Wallowa mantle anomaly thought to be delaminated Farallon lithosphere. The ambient noise and earthquake surface wave tomography will address our project goals by: (1) imaging any magma chamber in the
Wallowa-area crust and (2) improving receiver function and body-wave tomography studies (beneath the line array and regionally) by refining crustal velocity estimates (e.g., Shen et al., 2013).

The body-wave tomography will improve regional $V_p$ and $V_s$ models of the upper mantle to ~1000 km depth, with the goal of better resolving the geometry and seismic amplitude of the Wallowa mantle anomaly. The excellent resolution on crustal and Moho structure enabled by recent crustal studies (Shen et al., 2013; Gao et al., 2011), in conjunction with our own studies, will be an important part of improving the mantle imaging.

A better understanding of this anomaly will lead to refinements in our understanding of the proposed delamination of Farallon slab and its relation to Wallowa pluton root foundering. It also will provide the best possible images for any future geodynamic modeling (this modeling is included in a separate proposal that includes Humphreys). Our body-wave tomography incorporates 3-D ray tracing (Bezada et al., 2013), finite-frequency sensitivity kernels, and joint P and S inversion as in Schmandt & Humphreys (2010a). Two significant advances will improve image quality considerably since the Wallowa anomaly was last imaged (Darold & Humphreys, 2013). First will be the addition of the ID-OR data, all of the High Lava Plains data, and data from our line array. Second is the use of 3-D ray tracing (Bezada et al., 2013). We developed this improvement to better image steeply-dipping high-velocity structure (the Gibraltar slab), and found the width of the slab imaged with standard ray tracing was artificially widened by ~50%. A similar improvement is expected in the image quality of the Wallowa anomaly.

**Petrologic Studies**

Critics of a mantle plume origin for the CRB (e.g., Hart and Carlson, 1987; Foulger, 2007; Long et al., 2012 and refs. therein) have long questioned the lack of primitive basalt in the CRB stratigraphy. Such basalts should have high Cr content, highly magnesian olivine, and low silica content, all of which would be consistent with relatively high melt fractions of mantle peridotite. Although one may attribute the surficial absence of these relatively high density lavas to underplating and lithospheric injection, thereby creating conditions ripe for assimilation and delamination, the presence of minor amounts of olivine basalt having chromium spinel inclusions and Fo$_{86-84}$ olivine (Nicolaysen, unpublished) near the margins of the Wallowa anomaly requires careful consideration and analysis (Fig. 9). Moreover the presence of odd, highly sodic olivine-bearing lavas a scant 3 million years later with equilibrium olivine compositions of Fo$_{75-78}$ (Nicolaysen, unpublished) is problematic given that contemporaneous Saddle Mountains Basalts grouped with the CRB continued to erupt within ~100 km to the north.

Recent papers by LeRoux et al. (2010, 2011) testify to the potential of minor element abundances (Zn, Mn, Fe, Ni, Cr), both in bulk rock and in olivine minerals, to discriminate between peridotite source melting and eclogite source melting during magma genesis. Because either the margins of a ripped slab (e.g., Liu & Stegman, 2012) or delaminating lithosphere (e.g., Darold and Humphreys, 2013) predict that eclogite should be newly in contact with a hot upwelling asthenosphere of a putative mantle plume, the minor element compositions of the olivine provide an appealing test to support or disprove these models.

As part of an exploratory project (NSF-funded REU supported by the Keck Geology Consortium [see www.keckgeology.org/26th-keck-symposium-volume]), Nicolaysen and student acquired 7 samples of the Powder River Volcanic Field basanites, most of which were drilled and a few of which intersect crustal xenoliths, and 5 samples of the Little Catherine Creek olivine basalts. Nicolaysen acquired bulk rock major and trace element XRF data, oxygen isotope data on olivine separates, and Sr, Nd, Pb, and Hf whole rock isotopic compositions. Although we have robust major element analysis on two samples, one basanite and one olivine basalt, we did not fully characterize the minor element abundances of the olivine. Also, a more definitive test of the hypotheses set forth in this proposal will require analysis of more samples. Initial data are compelling (Fig. 9), particularly in that the whole rock Sr/Y and Zn/Fe of the basanites may be attributed to partial melts of eclogite contributing to the magma.
Work plan

1. Deployment of the seismic instruments will begin in early summer of 2016, supervised by Pat Ryan (Univ. of Oregon). Installation crews will be supplied by Oregon and Caltech, and with participation by undergraduates from the Keck Geology Consortium. Deployment duration is 1.5 years. Broadband seismometers will be inspected and serviced one month later, and then every 3 months thereafter. The dense array will be deployed when the equipment becomes available, and will be retrieved a month later.

2. Postdoc Sara Dougherty will lead the receiver function imaging effort. She will reside at the University of Oregon (although she will be paid through Caltech because it is less expensive). A Caltech graduate student will lead the tomography effort, with frequent visits to University of Oregon to learn our code and to interact with us. Caltech undergraduates will work on the ambient noise correlations, and a Keck-sponsored undergraduate at the University of Oregon will work on the SKS-splitting analysis.

3. Kirsten Nicolaysen (Whitman College) will do her geochemical analysis in year 1 of this proposal. In all three years she, Andrew Horst (Oberlin College), and Eugene Humphreys will work with undergraduate students (one student per institution) under support from the Keck Geology Consortium.

4. The integration of results will be coordinated in joint meetings at Oregon and Caltech, and at national AGU meetings. Postdoc Sara Dougherty and the Caltech graduate student will make visits to their non-home institution at least once a year, and Kirsten Nicolaysen will make a visit to the University of Oregon. Eugene Humphreys will visit Whitman at least once a year, in conjunction with fieldwork. The most useful means of keeping abreast of each other’s work and coordinating our research efforts will be frequent use of Skype meetings.

Broader Impacts

Although focused on a specific example in the Wallowa region of Oregon, our project will have implications for most founding and flood basalt events and will introduce magmatism as an efficient mechanism for founding. It also has important implications on epeirogeny, continental lithosphere creation and modification, and mechanisms for lithospheric amplification of flood basalt events.

The project will further the careers of one graduate student at Caltech and postdoc Sara Dougherty, a recent Caltech graduate. Undergraduate involvement will include Caltech undergraduates in research through the SURF (Summer Undergraduate Research Fellowship) program that provides, in addition to faculty-student research interaction, an environment in which the students give written and oral presentations of their work. The Caltech undergraduate research will focus on ambient noise correlation and the use of extracted surface and P waves to develop a crustal model.

Our most concerted effort with undergraduate students will be a three-person, three-year REU project within the organizational structure of the Keck Geology Consortium. This will involve undergraduate students and faculty in our fieldwork and scientific research. Schools participating in this project are Whitman College (under the direction of co-PI Kirsten Nicolaysen), Oberlin College (see supporting letter from Andrew Horst), and the University of Oregon. Because Whitman College is within our field area, the opportunity for student involvement is strong.

This project will bolster the geophysics graduate opportunities for Whitman and Oberlin undergraduates in several important ways. First, it will involve direct interactions with PIs Humphreys and Clayton, thereby increasing the awareness of graduate opportunities at Univ. Oregon and Caltech. Second, undergraduate students at Whitman and those who participate in the Keck Geology Consortium REU will engage in installation of the geophysical equipment necessary for this project, getting hands-on experience with seismic fieldwork. Third, those students involved in the associated Keck Geology Consortium project will participate in an intellectually-stimulating, multidisciplinary research experience (funded by NSF’s REU program) for their senior theses (see the supporting letter from Andrew Horst for some preliminary ideas). These students will have the opportunity to experience actual, meaningful
scientific research. Fourth, students at Whitman will benefit from annual presentations and a 1-week ~24-student seminar (on seismology, tectonics, or geodynamics) on their campus by PI Humphreys.

Results from prior support [shows supported student]

E. Humphreys. EAR-952194, Collaborative Research: Multiscale travel time tomography of Earth’s mantle to 1000 km depth beneath western U.S., $104K, 2010-12 (coPI, R. van der Hilst).

Intellectual Merit. Tomography of western U.S. upper mantle and crust, using P and S body waves, receiver functions and ambient noise, and interpretations for western U.S. history. We (1) found that the Farallon slab that subducted beneath western U.S. is dismembered, with many fragments of the Laramide-age slab still attached to North America, (2) convincingly imaged Yellowstone to overlie a bulbous lower mantle plume, and (3) synthesized a Cenozoic history for the Pacific Northwest, which is dominated by the effects of Farallon lithosphere accretion (including Siletzia) and subsequent foundering around its margins. Much of this work helps place the Pacific Northwest meaningfully into the tectonic evolution of the western U.S.

Broader Impact. Research largely or partly supported PhD students Haiying Gao, Brandon Schmandt, and Leland O’Driscoll, and M.S. student Amberlee Darold, leading to publication of the following ten papers on seismic structure, geodynamics, and geologic history, half of which focused on the Pacific Northwest. Included is a general article on mantle plumes in Physics Today. Darold & Humphreys, 2013; Schmandt et al., 2012; Humphreys & Schmandt, 2011; O’Driscoll et al., 2011; Levander et al., 2011; Gao et al., 2011; Schmandt & Humphreys, 2011; Adams & Humphreys, 2010; Schmandt & Humphreys, 2010a; Schmandt & Humphreys, 2010b.

R. Clayton. EAR-1045683, Collaborative Research: The Peru Subduction Zone Experiment (PeruSE), a Seismic Investigation of the Role of Water in the Lithospheric Dynamics of Subduction Zones, $172K, 03/01/2011-03/01/2013.

Intellectual Merit. The flat-to-normal slab dip regime in southern Peru is imaged with dense linear arrays of broadband stations. The key discoveries are a pervasive mid-crustal interface beneath the high Andes that is interpreted as underthrusting of the Brazilian Shield, and a continuous transition between steep and shallow subduction (rather than a tear) despite the abrupt change in slab dip.

Broader Impact. This study has so far resulted in five publications: Phillips et al., 2012; Ma et al., 2013; Phillips & Clayton, 2014; Ma & Clayton, 2014, and Dougherty & Clayton, 2015. Research from this project is the basis of a PhD thesis (Kristin Phillips), and a major part of two others (Yiran Ma & Sara Dougherty). The PI led a class trip (with private funding) to the field area (southern Peru) that included 6 undergraduate and 12 graduate students. The data from this experiment will be sent to the IRIS-DMC in late-2015. Parts of the data are being shared with three other groups conducting research in this region and with the Institute of Geophysics in Peru.


Intellectual Merit. The Islands of Four Mountains region holds the key to revealing the natural and human dynamics involved in the westward human settlement of the Aleutians. Aleutian research as a whole has failed to integrate the impacts of sudden geological and gradual environmental changes on subarctic human society. Major results: discovery of a major welded rhyolitic tuff, geochemical characterization of prehistoric lithic tools, characterization of unconsolidated sediments interbedded with cultural layers, mapping and geochemical analyses (XRF, ICP-MS, EPMA) of samples from three previously unstudied volcanoes (Tana, Carlisle, Herbert) plus supplementing Nicolaysen’s ongoing research at Mt. Cleveland.

Broader impacts. Through partnerships with the USGS, Alaska Volcano Observatory, Museum of the Aleutians, the Keck Geological Consortium, and the Aleut Corporation, this project brings together the government agencies focused on hazards monitoring, the academic research community, Native Americans, students, and policy makers. In year 1, three undergraduate research students (Lydia Loopesko, Thomas Bartlett III, Anne Fulton) completed both the ~1 month field season and senior
research theses. Middle school students on Unalaska, AK, participated in sample exploration. Public presentations occurred at the Museum of the Aleutians (7/14) and the Seattle Science Center (3/15). At this point, results are disseminated 3 archeology-related conference papers presented in 2015: Fulton, Izbekov, Lackey, & Nicolaysen, 2015; Neal, Izbekov, & Nicolaysen, 2015; Okuno, Fulton, Loopesko, Izbekov, Nicolaysen, Hatfield, West, Bruner, Savinetsky & Krylovich, 2015.

Figures

Fig. 1. Structural relations in the Wallowa area. (a) Reference map, showing seismic stations (from Fig. 5). Small white rectangle shows location of proposed high-density array. (b) Topography. Larger ellipse is the outer limit of the topographic bullseye; inner ellipse locates the Wallowa Mts. Note similarity to the uplift field in (d). This topography represents changes in buoyancy structure, presumably associated with root foundering at its center. (c) Moho depth, showing a 15-km depression where the Wallowa mantle anomaly meets the crust. (d) Uplift of the once-flat Grande Ronde flows of the Columbia River flood basalts (CRB). The Wallowa pluton (W and fine line), and only this pluton, rose ~2 km above the surrounding area (Hales et al., 2005). This Mesozoic pluton is the largest in this area of few plutons, and its uplift almost certainly is a response to its root foundering. Lower panel shows 3 magneto-stratigraphically defined Grande Ronde flow interfaces. While most of the surface warping occurred after the CRB eruptions, occurrence of some warping during the eruptions indicates early crustal deformation in the bullseye area. (e) Tomographic image of high-velocity structures thought to be foundered Farallon slab fragments (Darold & Humphreys, 2013). Map-view image shows the CRB dikes (red lines). The large gray ellipse locates the topographic bullseye seen in Fig. 2c. The high-velocity structure beneath NE Oregon is thought to have delaminated ~16.5 Ma (Fig. 3). The high-velocity structure to its north and east is thought to have foundered ~50 Ma (Schmandt & Humphreys, 2011). (f) The western U.S. map puts the study area into a more general framework. Away from deep cratons in Wyoming and Montana, high-velocity structures represent cool downwellings created after Laramide flat-slab subduction. White dotted line highlights foundered Farallon slab (Schmandt & Humphreys, 2011). Our proposed study focuses on the circular structure outlined with the dashed line. White rectangle marks area shown in (e).
Fig. 2. Regional setting for the Columbia River flood basalts. (a) Timing of main erupted lavas. Percentages shown indicate fraction of the total flood basalt volume. (b) Map showing the eruptive centers (labeled in red) and the flood basalt dikes (dark blue; green where inferred from magnetic anomalies). The pattern of dikes and faults (black hachured lines) radiate away from the area of the dashed-yellow ellipse, interpreted by Wolff & Ramos (2013) (and others) as the site of a central magma chamber. Purple dashes show maximum horizontal stress orientation from Glen & Ponce (2002), who applied dilation (at the purple dashed circle) to a regional stress field. This represents the temporal evolution hypothesis, in which the system evolves within this magma chamber and eruptive centers are fed by phases of diking. The dashed-red ellipse locates the topographic bullseye in (c). Yellow shading shows area covered by flood basalts; light blue line is the western edge of the Precambrian crust (the “Sr .706 line”).

Fig. 3. Model for two delaminations and magmatism in eastern Oregon, based on mantle tomography, uplift patterns, and the tectonic and magmatic history (Darold & Humphreys, 2013). A fragment of Farallon lithosphere (green) was left at the base of North America after the Laramide orogeny. Yellowstone plume arrival (top) triggers slab delamination, and its rollback draws hot plume asthenosphere (and volcanism) north. When the slab falls away from an old pluton, its root (dark purple) begins to founder, initiating Wallowa pluton uplift (eventually to 2 km). Melt drawn into the evacuating space and heating at the exposed base of the crust produces the large Grande Ronde eruptions at this time and location. This causes melting of crustal rock (to account for the magma chemistry, Fig. 4), shown here as a combination of the oceanic crust atop the foundering Farallon slab and the lower to middle continental crust. This figure represents the spatial evolution hypothesis; system evolution is driven by northward propagating rollback. Delamination and magmatism define an interactive system with each enabling the other.
Fig. 4. Columbia River flood basalt chemistry. (a) Evidence for three distinctive sources (from Wolff & Ramos, 2013). The important point is that an initial composition (IC) is identified and is represented by Imnaha lava (red circles), which is dominated by the Yellowstone plume. Grande Ronde lava (green squares) incorporates an Archean crust component (“ID batholith”), and Steens (blue triangles) and Monument (orange diamonds) lavas are mixed with a MORB-like component. (b) Plot showing the anomalous basaltic-andesite composition of Grande Ronde lavas (Camp & Hanan, 2008). This composition cannot be a primary mantle melt. Various models have the Yellowstone plume either assimilating large volumes of lower crust (e.g., Wolff & Ramos, 2013) or melting a basalt-like rock at the source (e.g., Takahabashi et al., 1998) to generate the anomalous basaltic-andesite lavas.

Fig. 5. Seismic stations near our study area. Stations shown include: Wallowa (red dots), ID-OR (orange circles and black line with stars for active component), High Lava Plains (purple circles), EarthScope TA (blue circles), and permanent (green circles). Prior tomography used only a fraction of the High Lava Plains seismometers, and none of the ID-OR seismometers. Our proposed linear array is shown with 40 small yellow dots, spaced at ~4 km. Insets show the dense deployment of 200 high-frequency seismometers spaced at 100 m. Black ellipses as in Fig. 2.
Fig. 6. Receiver function data and simulation of target region. (a) P-to-S receiver functions (from Wallowa array) gathered by station and ordered by back azimuth. Note receiver function stability and back-azimuth variation, indicative of high-quality data and short-wavelength structure. (b) S-to-P receiver function stack (figure courtesy of E. Hopper & K. Fischer). Small orange arrows show limits to the bullseye area. A lens-shaped crustal structure is imaged beneath the southern 70% of this area and is unique to the bullseye. Profile is along the white dashed line in (d). (c) The middle two panels show a P-to-S receiver function profile calculated by stacking synthetic receiver functions over a range of azimuths. Calculation done with finite-difference simulation of model with a magma chamber of similar size and complexity as the one we plan to image (top panel). The receiver function images are shown at two densities: 4 km spacing (this proposal) and 12 km (the present data). A back-azimuth stack of the actual data is shown in the bottom panel. While this indicates the presence of the target, it does not resolve it well enough for interpretation, as a 4-km survey would. (d) Location map.

Fig. 7. Including scattered phases in receiver functions. The bottom panel shows a common conversion point migration of Ps converted phases, while the top shows the image using the phase PpPp. In the top image, the slab is much more clearly delineated, and the slight upward dip to the right is much more clearly evident. This example is from the PeruSE experiment (Phillips & Clayton, 2012) in southern Peru and part of a paper by Ma & Clayton to be submitted in mid-2015.
Fig. 8. Autocorrelations of high-frequency ambient noise (mostly wind noise). Data are from a tight cluster of 24 geophones. Each trace is the summed autocorrelation, each for a 15-min duration during 18 hours. Data are filtered with a Gaussian filter of center frequency 8 Hz and half-width 6 Hz. Data from Newberry volcano. (figure courtesy of E. Hooft and B. Heath).

Fig 9. Preliminary EPMA analyses of olivine in the olivine basalt (red squares) and in the basanite (black circles) obtained using the SX50 at the Univ. Oregon Camcor facility. Olivine in all three samples are in equilibrium with their host magmas or the analyses would plot outside of the analytical envelope shown by dashed lines. The olivines in the olivine basalt have Cr spinel inclusions (a) and high magnesian compositions (Fo84-86), both testifying to the primary nature of the host basalt. The larger skeletal olivines (b) in the basanite have Fe-Ti oxide inclusions rather than high Cr spinel inclusions, and they have Fo75-78 compositions. These samples are suitable for subsequent analysis of additional minor element (Mn, Al, Ca, Ti, Zn, Cr, Ni) abundances that are diagnostic for peridotite versus eclogite magma sources. Semi-quantitative SEM EDS data obtained for two additional samples suggest acquisition of a robust data set to test the proposed models is quite feasible.
Adams, D, & Humphreys, E, 2010, New constraints on the properties of the Yellowstone mantle plume from P and S-wave attenuation tomography, *JGR.*, 115, B12311.


Lin, FC, Li, D, Clayton, R W, & Hollis, D, 2013, High-resolution 3D shallow crustal structure in Long Beach, California: Application of ambient noise tomography on a dense seismic array, Geophysics, 78(4), Q45-Q56.


O’Driscoll, LJ, 2007, Geochemical evidence for a dense mafic root of units in the Wallowa batholith, Wallowa Mountains, northeastern Oregon, GSA Abs with Programs, 39, 290.


