Collaborative Research: Understanding the Causes of Continental Intraplate Tectonomagmatism: A Case Study in the Pacific Northwest

1) INTRODUCTION

Magmatism in intracontinental settings represents a major unresolved problem in continental dynamics. Unlike mid-ocean ridge and subduction-zone settings where we have a first-order understanding of the dynamic processes responsible for magma generation and crust production, we have no such governing paradigms for the tectono-magmatic processes at intraplate settings. This proposal outlines a multi-disciplinary study of an excellent (archetypal) example of an intraplate magmatic environment that is one of the great continental volcanic provinces on Earth (Fig. 1). Our area of interest spans about 400 km from the Cascades arc eastward across an amalgam of accreted terranes in eastern Oregon to the Precambrian craton in Idaho and from nonextended and amagmatic accreted crust in central Oregon about 250 km to the south into the northern Basin and Range Province of southern Oregon and adjacent Nevada. We call this vast area the High Lava Plains [sensu lato; cf., *Christiansen and McKee*, 1978], which, along with the Snake River Plain, has been the most volcanically active part of North America in the late Cenozoic (Fig. 1).

The complex tectonomagmatic evolution east of the Cascades has been variously ascribed to a variety of plate-boundary causes including back-arc spreading [*Christiansen and McKee*, 1978], Basin and Range extension [*Cross and Pilger*, 1978] and asthenospheric inflow behind a steepening subducting Juan de Fuca plate [*Carlson and Hart*, 1987]. Given the extraordinary volume of volcanism in this area and the plate motion directed migration of volcanism up the Snake River Plain, the notion of a deep mantle plume has gained popularity as an alternative "external" cause of the volcanism [e.g. *Geist and Richards*, 1993; *Camp and Ross*, 2004]. All these various models have been developed over the last 30 years based largely on the geologic, geochemical and geochronologic study of the surface volcanism in this area. What is notably absent, but is critical for resolving the true cause of magmatism in this area, is information on the crustal basement and upper mantle structure that underlies the veneer of late Cenozoic volcanic rocks that completely covers most of southeastern Oregon. The four broad questions of concern in explaining the magmatism in southeastern Oregon are the same as those related to the general causes of continental intraplate tectonomagmatism:

1. Is a plume the only way to get large-volume aerially extensive intraplate volcanism?
2. Does flow of mantle around the edges of a retreating or "dying" subducting plate instigate focused volcanism in the overlying crust of the back arc?
3. Can the bottom topography of the lithospheric mantle influence flow in the underlying mantle to the point of localizing tectonomagmatism in the overlying crust?
4. Is crustal extension the cause or expression of continental magmatism?

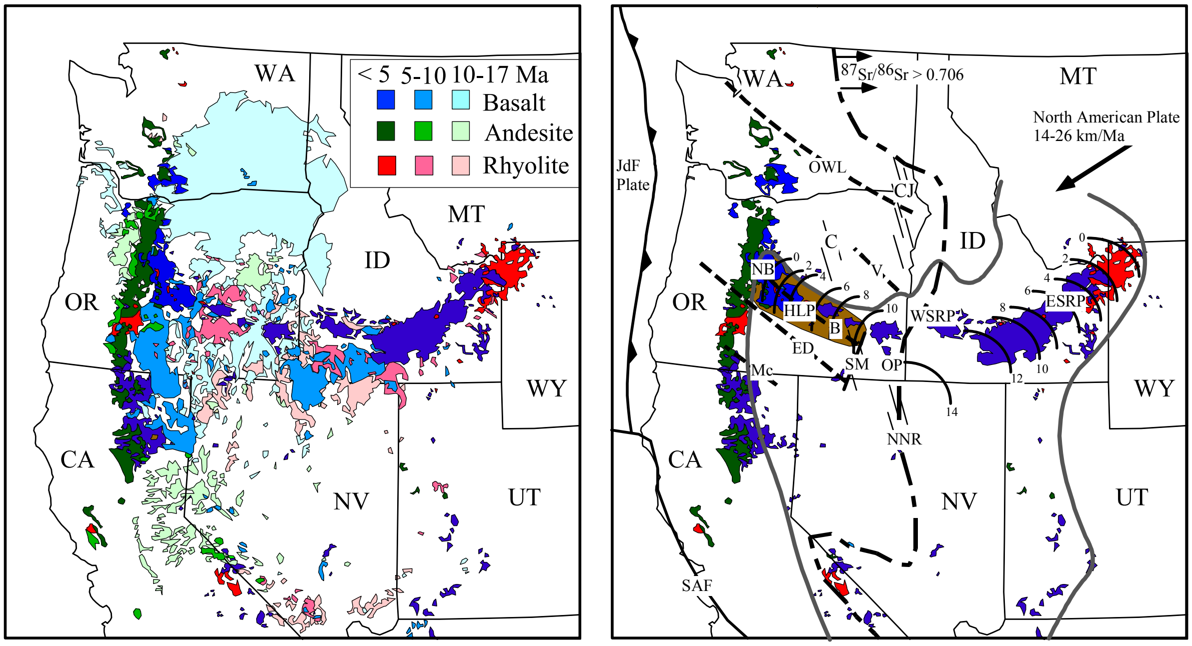


Figure 1: Volcanic [after *Smith and Luedke*, 1984] and tectonic [after *Streck et al.*, 1999] elements of the Pacific Northwest. Left panel shows post 17 Ma volcanic deposits to illustrate the tremendous volcanic activity east of the Cascades in the northern reaches of the Basin and Range (outlined by thick grey lines on right panel). The right panel shows only sub-5 Ma volcanic fields to illustrate the continuing activity in the Cascades and along both the High Lava Plains (HLP ñ brown field) and the Eastern Snake River Plain (ESRP). Short curves along the ESRP and HLP are isochrons (ages in Ma) for the migrating silicic volcanism along each volcanic trace. Flood basalt activity was fed from dike systems in the Northern Nevada Rift (NNR), Steens Mtn. (SM), the Western Snake River Plain (WSRP) and the Chief Joseph (CJ) and Cornucopia (C) dike swarms of the Columbia River basalts. With the exception of the Cornucopia swarm, these dikes occur near the western border of Precambrian North America as defined by the 0.706 line (large dot-dash line). Dotted lines show NW trending fault systems: Olympic-Wallowa Lineament (OWL), Vale (V), Brothers (B), Eugene-Denio (ED) and McLoughlin (Mc). Additional features shown include Newberry Volcano (NB), the Owyhee Plateau (OP), Juan de Fuca Plate, and San Andreas Fault (SAF).

1.1) OVERVIEW OF PROJECT STRUCTURE, GOALS, AND INTEGRATION

Existing geologic, geochemical, and geochronologic information on the surface volcanism provides the basis to suggest that the High Lava Plains is the best, currently active, example worldwide in which to study the causes of widespread intraplate continental volcanism. This four-year, multi-institutional, interdisciplinary project will have four major components; seismology, experimental petrology, geochemistry and geodynamic modeling. The collaborative research will produce:

- The first high resolution images of crustal and upper mantle structure beneath the High Lava Plains
- The first experimental petrological study of primitive basalts spanning the wide compositional range observed from the Cascades to the Snake River Plain
- New geochemical and geochronologic studies targeted specifically to improve estimates of spatio-temporal variations in volcanic volume and the role of subduction-derived fluids/melts in magma genesis
- Geodynamic models of mantle flow patterns expected for the complicated mantle structure present in this area that may include any or all of: a plume, a retreating slab,

a migrating southern edge to the slab, and significant topography on the base of the lithospheric mantle

The way we view the various disciplinary components of this project interacting is shown schematically in Table 1. While each of these components could be performed separately, this approach already has been followed for the last 30 years in western North America with diminishing progress. We suggest that a fundamental improvement in our understanding of the causes of large-scale intraplate continental volcanism, as exemplified in the Pacific Northwest, requires the connection between the surface volcanic record, the mantle conditions necessary to produce these magmas as determined by geochemistry and experimental petrology, and high-resolution images of crustal and mantle structure, all of which are placed into a geodynamic model of sufficient detail to incorporate and help interpret the connection between the various data types. This is what we propose to do in this project.

Table 1: What process(es) lead to voluminous continental intraplate volcanism?

Evidence**:** ***data***	**Geodynamics**	**Seismology**	**Geochemistry**	**Petrology**
Plumes	Mantle flow patterns and spatio-temporal migration of melting: ***Numerical and laboratory modeling to predict mantle temperature and anisotropy***	Mantle flow patterns, upper mantle 3-D temperature structure, detection of plume conduit: ***Shear wave splitting*** **anisotropy**, ***Vp, Vs tomography from teleseismic deployments, including USArray***	Location, timing, and source composition of magmatism: ***Existing and new information on spatio-temporal history of volcanism***	3-D picture of melting depths and temperatures: ***New experiments to define melting pressure and temperature of primitive basalts***
Mantle flow related to subduction	Nature of flow around slab edge and into gap created by retreating plate: ***Numerical and laboratory modeling based on imaged structure. Past work on slab flow modeling***	Upper mantle 3-D temperature structure, position of subducting slab and its southern edge: ***Vp, Vs tomography and receiver function migration from teleseismic deployments, including USArray***	Degree of melting, source materials, role of introduced slab components: ***Existing data with new data on elements sensitive to slab contribution***	Influence of H_2O on pressure and temperature of melting: ***New experiments to explore*** H_2O ***effects on magma genesis***
Mantle lithosphere structure	Consequences of observed structures on flow in the underlying mantle: ***Laboratory modeling of asthenospheric flow perturbations caused by imaged topography***	Images of lithosphere structure and basal topography: ***Vp and Vs tomography from teleseismic deployment, Moho depths from active seismic imaging and receiver functions***	Degree of melting, history of source materials: ***Existing spatio-temporal data on composition and volume variation with expanded data near terrane boundaries***	Melting depths, temperatures and processes: ***New experiments on primitive basalts from near terrane boundaries***
Crustal influence		Moho structure/depth, amount of magmatic under- intraplating: ***Receiver function and active seismic imaging***	Crustal contribution to magmas: ***Analysis of crustal xenoliths, xenocrysts, modeling fractionation, assimilation***	Crustal level fractionation: ***Expectations for crystallization sequence***

1.2) *THE INVESTIGATIVE TOOLS*

The greatest hindrance to understanding and testing ideas about the processes causing widespread magmatism in the High Lava Plains is the lack of detailed geophysical information on crust and upper mantle structure and how these structures relate to the Cenozoic volcanic record. Other regions of the western US, particularly the Snake River Plain - Yellowstone area, have been the subjects of several recent geophysical imaging projects [*Saltzer and Humphreys*, 1997; *Schutt et al.*, 1997, 1998; *Peng and Humphreys*, 1998; *Humphreys et al.*, 2000; *Christiansen et al.*, 2002], but eastern Oregon remains largely uninvestigated geophysically. We propose to carry out seismic imaging at three levels of resolution (Fig. 2). Broad regional coverage will be provided by analysis of data from the transportable component of USArray [*Meltzer et al.*, 1999]. This wide area image with relatively low resolution will illuminate features of the High Lava Plains lithosphere as they relate to broader scale features of the western US including the subducting Juan de Fuca plate. Higher resolution images of upper mantle structure and anisotropy will be provided by dense arrays, both linear and 2-D, of broadband seismometers (Fig. 2). These dense arrays include: (1) two closely spaced (~15 km) linear deployments to enable continuous and unaliased imaging of deep discontinuity structure; and (2) sixty stand-alone broadband deployments in densified swaths (station spacing ~ 20ñ30 km) along the two major transects to enable high-resolution tomography to depths in excess of 300 km. An embedded active-source refraction array will provide still higher resolution images of crustal velocity structure. Both the broadband arrays and embedded active-source refraction lines are sited to provide the best imaging of the mantle and crust directly beneath the trace of volcanism along the High Lava Plains and across the four distinct terrane boundaries surrounding the High Lava Plains. To assist in interpreting the seismic structures imaged in the crust, gravity measurements along the seismic refraction lines will further constrain the density and hence compositional structure of the crust, particularly near major volcanic centers. This information is essential in order to obtain accurate estimates of spatio-temporal variations in the volume of magmatism; a key input parameter to geodynamic modeling that will examine the mantle melting consequences of flow in the mantle caused by a plume, a retreating slab, and around the southern edge of the "dying" Juan de Fuca plate, in an attempt to correlate the surface volcanism with features of the underlying mantle that ultimately may be responsible for the volcanism.

These geophysical tools, guided by the physical modeling component of this project, are directed at key targets using the background of geological, geochemical, and geochronological information obtained by a subset of the PI's, and others, through past work in this area. We do not intend to duplicate previous field and geochemical study of the volcanic rocks in this area, but we do intend to add some components to this dataset that are of critical importance as input into the geophysical and geodynamic aspects of this project. One such component is improved geochronology of the young volcanism in order to better define the pattern of volcanic volume versus time and position that will be an important parameter to compare with both seismic images and particularly geodynamic models. Another component is experimental petrological investigations of primitive basalts coupled with measure of their volatile (H_2O, CO_2) abundances and other tracers (Ba, Nb, Ta, Cl abundances and B isotopic composition) sensitive to the presence of subduction fluids/melts in the source of these magmas. Information on the pressure, temperature, and water content in the magma's mantle sources will provide a critical calibration of the temperature structure in the upper mantle as inferred from teleseismic tomography. Finally, we will obtain data on subsurface crustal rocks through analysis of the rare xenoliths of upper crust, xenocrysts of zircon and feldspar contained in some of the silicic volcanic rocks, and petrologic modeling of crustal magma sources and their compositional variation with time. These data will constrain seismically determined crustal velocity/density structure and how the crust of the High Lava Plains has been modified by the extensive Cenzoic magmatism.

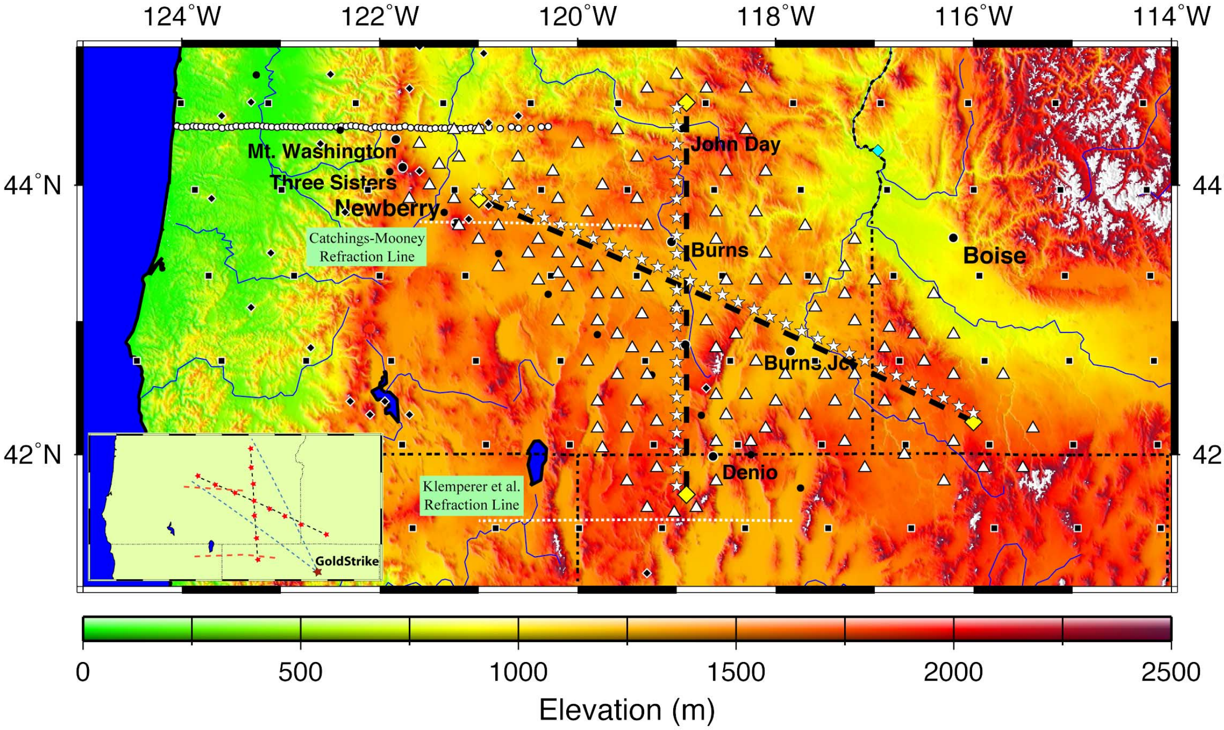


Figure 2: Map showing station locations overlain on color-coded topography in southeastern Oregon. A total of 92 broadband (REFTEK/STS-2 or equivalent) seismograph units will be used in two separate deployments over a two-year period. The broadband instrumentation consists of 32 telemetered stations (white stars) and 60 stand-alone stations (white triangles). (Note: for ease of discussion we use the term ìtelemetered arrayî for these deployments. Logistical restrictions make it likely that these dense profiles will consist of both telemetered and stand-alone instruments). Approximately 170 broadband sites will be occupied during the course of the experiment, with ~30 sites duplicated to provide anchor points at the crossing between the two transects. The first year deployment will be along the NW-SE transect, the second year deployment will be along the crossing N-S transect. The axes of the two broadband transects (instrument spacing ~15 km) coincide with and complement the refraction/reflection lines. This geometry will allow for continuous, unaliased, high-resolution imaging of discontinuity and anisotropy structure within both crust and upper mantle. The 2-D array is of sufficient aerial extent (~500x350 km) to assure that tomographic structures can be well resolved from the uppermost mantle and lowermost crust to depths in excess of 300 km. The refraction/low-fold reflection profiles are shown as heavy black dashed lines. Black squares denote USArray Transportable Array (Bigfoot) stations, scheduled for installation in 2006. The closely spaced open circles that form the east-west profile from the Pacific coast across the Cascades mark stations of the Cascadia broadband experiment [*Nabelek et al.*, 1993]. Small black circles are nominal sites of a reconnaissance broadband experiment led by Richard Allen (U. Wisconsin). Small white diamonds denote regional network sites comprised mostly of short period instruments. Labeled dotted yellow lines indicate previous active source experiments across Newberry and northern Nevada.

2) GEOLOGIC SETTING AND HISTORY OF THE PROPOSED STUDY AREA

The area targeted for this study is the region bounded to the west by the Cascades, to the north by the non-extending accreted terrains of the Blue Mountains, and to the east and south by Precambrian North America (Figs. 1, 3). In this area, the western margin of Precambrian North

America is clearly resolved only along the western Idaho shear zone, a steep structural boundary near the Idaho-Washington border that is coincident with an abrupt change in the initial ^{87}Sr/^{86}Sr of Mesozoic and Cenozoic magmatic rocks from < 0.706 west to > 0.706 east of the western Idaho shear zone [*Armstrong et al.*, 1977; *Manduca et al.*, 1992]. Elsewhere, the location of the Proterozoic cratonic margin is more enigmatic, but can be inferred from the location of the "0.706 line" (Figs. 1, 4). Pre-Cenozoic crust west of the craton margin is exposed in northeastern Oregon and westernmost Idaho and consists of Paleozoic-Mesozoic oceanic volcanic arcs, accretionary prism complexes and associated basinal successions accreted to western North America during Jurassic arc-continent collision [e.g. *Dickinson,* 1979; *Coney et al.,* 1980; *Oldow*, 1984; *Vallier*, 1995]. In the High Lava Plains, if this basement exists, it is completely covered by late-Cenozoic volcanic rocks.

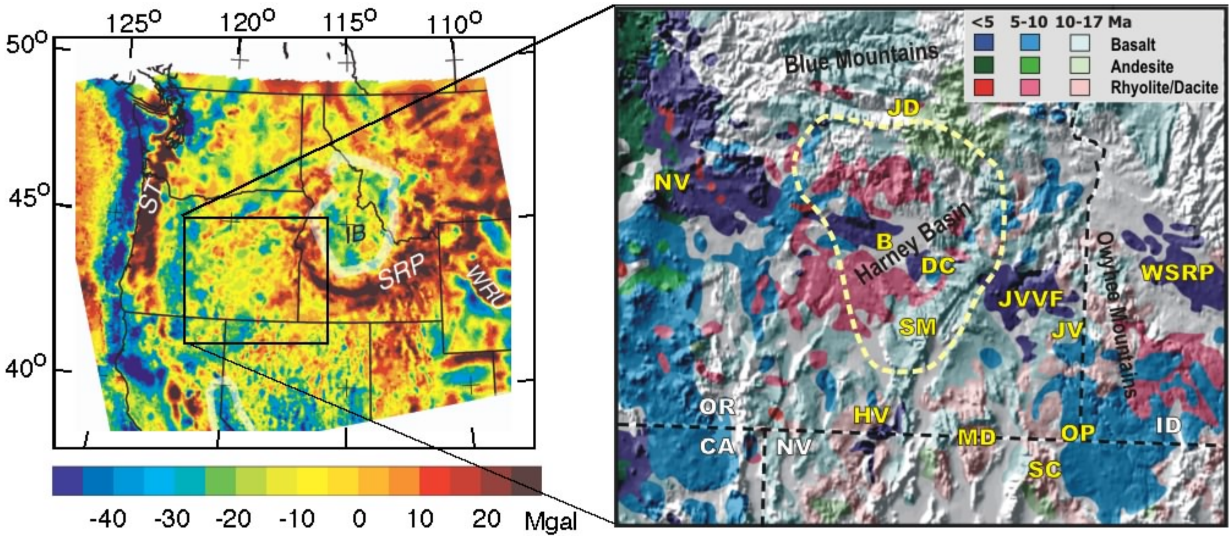


Figure 3: Residual isostatic gravity anomaly map for the northwestern US [*Keller et al.*, 2002]. The expanded map to the right shows the general volcanic geology depicted in Fig. 1 draped over a digital elevation model for the eastern Oregon region. The dashed outlined area depicts the approximate extent of the Devine Canyon Tuff. Abbreviated location names in yellow are: **NV** - Newberry volcanic field; **JD** - John Day; **B** - Burns; **DC** - Diamond Craters; **SM** - Steens Mtn.; **HV** - Hawkes Valley volcanic field; **MD** - McDermitt volcanic field; **JVVF** - Jordan Valley volcanic field; **JV** - Jordan Valley; **SC** - Santa Rosa-Calico volcanic field and northern portion of Northern Nevada Rift; **OP** - Owyhee Plateau; **WSRP** - western Snake River Plain.

Structurally, the High Lava Plains are dominated by a wide, diffuse zone of northwest-striking faults, the Brothers fault zone (Fig. 1). GPS data identify a point on the central Oregon-Washington border as the rotation axis for extension that increases southward into the Basin and Range [e.g. *McCaffrey et al.*, 2000]. Paleomagnetic estimates across 42° latitude suggest that eastern Oregon has been extended by about 17% during the last 15 Myr [*Wells and Heller*, 1988]. Fault systems like the Brothers are widely distributed in southeastern Oregon, but are concentrated in northwest-trending tracts (Fig. 1). The fault systems show right-lateral offset resulting from decreasing E-W extension to the north [Fig. 1, *Lawrence*, 1976]. Eastern Oregon, and the High Lava Plains in particular, thus mark the northern margin of Basin and Range related extension in western North America.

Western North America has experienced voluminous and aerially extensive magmatism throughout the Cenozoic that can be separated into three phases: the "ignimbrite sweep" characterized by large-volume eruptions of silicious magmas from centers migrating over much of western North America between 20-50 Ma [e.g. *Lipman et al.,* 1972]; the flood basalt episode between 17 and 15 Ma that involved the massive emplacement of dikes and the eruption of flood basalts along a ~700 km-long north-south line that follows the western margin of Precambrian North America [e.g. *Hooper*, 1997]; and finally, more distributed and generally bimodal (silicious and basaltic) volcanism along the margins of the Basin and Range (Fig. 1). During the third, still continuing, phase, the largest volumes of magma were erupted in the High Lava Plains and along the Snake River Plain. By about 12 Ma, volcanism in eastern Oregon became more clearly organized to form two migrating tracks, one moving at plate speed and plate direction to the northeast up the Snake River Plain towards Yellowstone [*Pierce and Morgan*, 1992] and the other moving in the opposite direction (WNW) at a similar rate along the High Lava Plains [*MacLeod et al.*, 1975; *Jordan et al.*, 2004]. Besides moving almost perpendicular to plate motion, the voluminous volcanism in the High Lava Plains trend is occurring at the northern margin of the Basin and Range where extension is minimal, thus precluding any clear connection between volcanic productivity and degree of lithospheric stretching. In some respects, this migrating track of silicic volcanism is a "mini" ignimbrite sweep similar to the much larger event occurring across North America in the early Cenozoic. The spatio-temporal progression is defined by silicic volcanism, that along the High Lava Plains is estimated to be about ten times less voluminous then along the Yellowstone track [*Pierce et al.*, 2000]. The migrating volcanic trace of the High Lava Plains ends today near the still active Newberry Volcano (Fig. 3). At the latitude of Newberry and the Three Sisters, the Cascade arc has unusually abundant Quaternary mafic volcanic rocks owing to youthful intra-arc rifting and has a fairly thin (35 km) and mafic crust [*Sherrod and Smith*, 1990; *Trehu et al.*, 1994; *Conrey et al.*, 2000]. The enhanced volcanic output of the Cascades near the intersection with the High Lava Plains suggests that whatever thermal anomaly caused the migrating volcanic trace is now contributing to volcanic output along the convergent margin. After passage of the silicic volcanic "front", volcanism persists along both tracks, erupting primarily basalt to the present day along most of the High Lava Plains and Snake River Plain with concentration of Quaternary activity at both ends of both trends - Yellowstone, Newberry, and the area surrounding the Owyhee Plateau in the Jordan Valley volcanic field (Fig. 3).

With the beginning of the High Lava Plains activity, basaltic volcanism shifted from the large-volume eruptions of differentiated basalt that typify the Steens-Columbia River flood basalts to be replaced primarily by primitive low-K, high Al, olivine tholeiite [HAOT - *Hart*, 1985] that shares many compositional similarities with mid-ocean ridge basalts (Fig. 4). This type of primitive basalt occurs throughout eastern Oregon [*Hart et al.*, 1984; *Conrey et al.*, 1997], along the Snake River Plain to Yellowstone [*Leeman*, 1982], and at various centers in the Cascades [*McKee et al.*, 1983; *Bacon et al.*, 1997], but is rare, if not absent, in the central and southern Basin and Range. Experimental petrological investigations of HAOT in the Cascades give a shallow mantle equilibration depth of 1.1 GPa [*Bartels et al.*, 1991] indicating that HAOT equilibrated close to the base of the crust. Recent low-resolution teleseismic studies of this area, however, reveal a low velocity region near 400 km depth that appears to correlate with the distribution of these primitive basalts at the surface [*Song et al.*, 2003]. Given the shallow equilibration depths inferred for the HAOT, this correlation with low velocities at the top of the transition zone mandates further investigation to understand its significance.

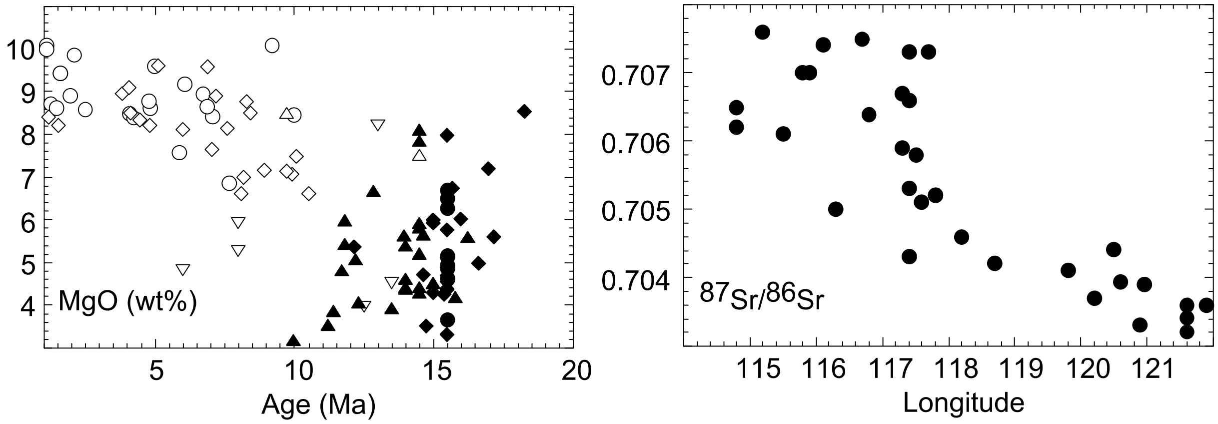


Figure 4: MgO vrs. Age and ^{87}Sr/^{86}Sr vrs Longitude for Cenozoic basalts from High Lava Plains. Steens basalts (filled symbols) tend towards low MgO whereas HAOT (open symbols on left panel) have more primitive, higher MgO compositions. HAOT (filled symbols on right panel) also display the strong regional variation in Sr isotopic composition shown by other magmas from eastern Oregon and clearly define the 0.706 line at ~117.5°W. Data from [*Hart et al.*, 1984; *Carlson and Hart*, 1987].

3) WHAT CAUSES VOLUMINOUS CONTINENTAL INTRAPLATE MAGMATISM?

The late Cenozoic history of eastern Oregon has been far from that typical of stable continental lithosphere. Eastern Oregon marks the northern terminus of Basin and Range extension, is the site of the world's only Neogene flood basalt province, is still the most volcanically active portion of the Basin and Range (along with the Snake River Plain), and contains a migrating volcanic trace that is moving at high angle to the direction of plate motion. What are the characteristics of the lithosphere and underlying mantle of this area that has caused it to play this particularly active role in the plate boundary evolution of western North America?

Listed below are four outstanding questions, the answers to which may explain why volcanism has been so voluminous and so wide spread well behind the convergent margin in the Pacific Northwest. For each question we present our plan of investigation and the combination of techniques to be applied that we believe will provide particularly illuminating results relevant to these fundamental questions. The study sites obviously are focused on the specific problem of western US volcanism, but the general questions that will be addressed are relevant on the global scale as they are the basic questions behind the causes of continental intraplate volcanism.

3.1) *IS A PLUME NECESSARY?*

The role of a plume in Pacific Northwest volcanism has been debated for the last 30 years, beginning with the observation of plate direction migration of volcanism along the Snake River Plain and strengthened by the suggestion that all flood basalts derive from the melting of the huge bulbous heads of new plumes. The fact that the plume/no-plume debate continues [*Christiansen et al.*, 2002; *Camp and Ross*, 2004; *Jordan et al.*, 2004] in the western US suggests that the definitive data on this question have yet to be gathered. Though it pains a certain fraction of the PI list to say it, geochemical tests for a plume origin for Pacific Northwest volcanism are ambiguous [e.g. *Carlson et al.*, 1983; *DePaolo*, 1983; *Carlson*, 1984; *Carlson and Hart*, 1987; *Brandon and Goals*, 1988; *Hooper and Hawkesworth*, 1993; *Dodson et al.*, 1997; *Chesley and Ruiz*, 1998; *Jordan et al.*, 2000].

Direct imaging of a plume conduit extending into the deep mantle would be convincing proof of a plume. Detailed seismic imaging beneath Yellowstone, the current location of the hot-spot, however, as yet reveals no low-velocity conduit extending below 200 km depth and no deflection of the 670 km discontinuity consistent with hot mantle at this depth [*Humphreys et al.*, 2000, *Montelli et al.*, 2004]. Plumes do not have to be continuous from their point of origin to the surface, so the lack of detection of a seismically slow feature extending into the lower mantle is not definitive, but certainly is suggestive.

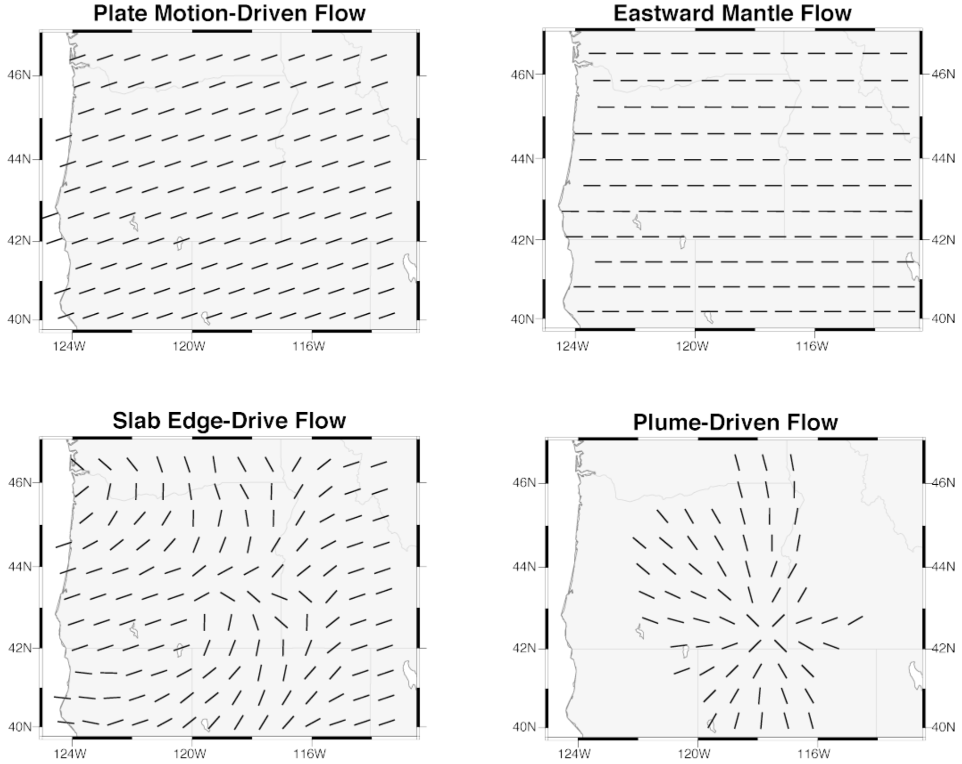


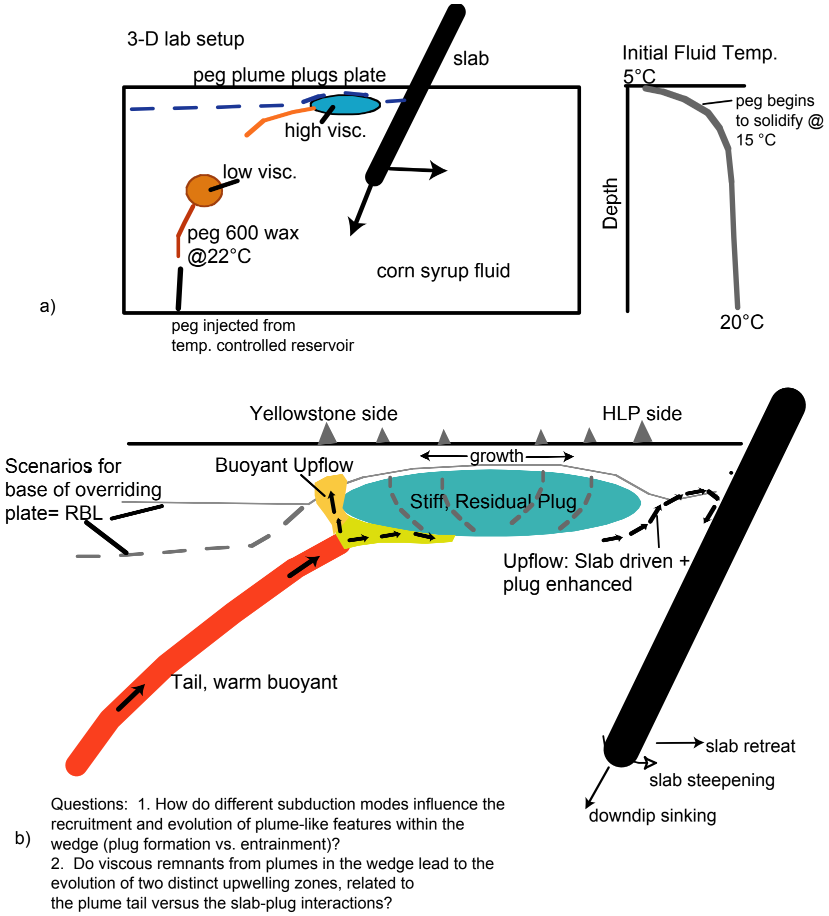
Figure 5: Predicted shear wave splitting observations for a range of proposed mantle flow models in the study region assuming that mantle anisotropy is the dominant signal for shear wave splitting in this region. These figures show distinctly different splitting patterns that distinguish between differing models of mantle flow in the study region. In all panels, black bars denote anticipated fast polarization directions for a given mantle flow field. A) Simple plate motion driven mantle flow. Absolute plate motion is calculated using the HS3-NUVEL1A plate motion model [*Gripp and Gordon*, 2002]. This mantle flow scenario should produce a simple pattern of ENE-WSW fast directions. B) Eastward mantle flow as extrapolated from that proposed by *Silver and Holt* [2002]. Such mantle flow should produce a simple pattern of E-W fast directions. C) Subduction edge-driven flow (see also models in Fig. 7). This mantle flow scenario should produce a complex, but quite diagnostic, pattern of shear wave splitting parameters. D) Plume outflow model. Predicted fast directions for this model are shown only for the regions indicated in Figure 9 of *Camp and Ross* [2004]. This mantle flow scenario should produce a complex pattern of shear wave splitting that differs significantly from that of model C, and which will be definitive of this plume outflow model.

There are two other imaging targets in eastern Oregon that potentially can address the role of a plume in causing the Cenozoic volcanism. First, plume models for the late Cenozoic magmatism suggest outflow of the plume head to the northwest in the direction of the High Lava Plains [*Draper*, 1991; *Camp and Ross*, 2004; *Jordan et al.*, 2004]. Such westward flow of the upper mantle is counter to that proposed on the basis of a comparison of plate motion and shear wave splitting parameters (fast polarization direction and delay time) for the western US [*Silver and Holt*, 2002]. Alternative mantle flow models for the High Lava Plains include plate-driven flow in the direction of absolute plate motion and subduction-induced edge-driven flow. Figure 5 shows a schematic predicted shear wave splitting for each of these possibilities. Currently, there are no published shear wave splitting measurements for virtually the entire Oregon and western Idaho region. To remedy a portion of this situation, PI Fouch [*Fouch*, 2004] is currently evaluating shear wave splitting data from the 1993-1994 Cascadia array (Fig. 2) with a range of analysis techniques not available during the original array deployment. However, to evaluate fully the competing hypotheses of inferred mantle flow fields across the bulk of the study region away from the convergent margin, we will determine shear wave splitting parameters for each of the broadband sites proposed here. The results from these analyses will allow us to compare in detail the predictions that result from the range of proposed flow models, which should be clearly resolvable from one another (Fig. 5).

3.1.1) Evaluating the consequences of plume-slab interaction

Another, less direct, imaging target relevant to the issue of plume involvement in northwestern US volcanism is the position of the subducting Juan de Fuca plate east of the Cascade chain. In the few million years preceding the arrival of flood basalt volcanism in eastern Oregon, calc-alkaline, presumably arc-related, volcanism was occurring as far east as the Oregon-Idaho border [*Norman and Leeman*, 1989]. This suggests the presence of the subducting plate at some 150-200 km depth beneath the area that was soon to experience flood basalt volcanism. If a plume caused the flood basalt volcanism, the plume had to penetrate the subducting slab, essentially dismembering this small remnant of the Juan de Fuca plate. Imaging the position of the subducting plate east of the Cascade axis thus is an important test not only of the plume model, but also is fundamental for testing ideas regarding the role of subduction in instigating High Lava Plains volcanism, as is addressed in the next section. The Juan de Fuca subduction system was well imaged by *Rondenay et al.* [2001], but only to depths of 120 km and only as far east as the Cascade front. The presence of a shallow dipping slab in the mantle beneath eastern Oregon would preclude any possibility that the volcanism in this area was caused by slab roll back. Finding a steep or discontinuous slab beneath eastern Oregon would be an ambiguous result regarding the role of a plume, but is a necessary observation for all existing non-plume explanations for this volcanism.

Given the apparent difficulty of imaging the top of the subducting plate with converted phases (receiver functions) at depths > 120 km [*Rondenay et al.*, 2001], tomographic methods will be key to imaging the deeper slab. We note in this regard, that global images such as *van der Lee and Nolet* [1997] exhibit little evidence for the descending Juan de Fuca slab beneath central and southern Oregon. A high resolution regional study involving dense local arrays of stations by *Bostock and VanDecar* [1995], however, found convincing evidence of a deep (>200 km), strongly arched, high velocity slab in the northern Cascadia subduction zone. There, the deep slab dips steeply (at angles > 45°) to the east (in northwest Washington) and NE beneath British Columbia, apparently extending to a depth of at least 400 km. If the slab beneath Oregon is similar in shape to that imaged to the north [*Bostock and VanDecar*, 1995], the array study proposed here should be sufficient to image its structure.



Questions: 1. How do different subduction modes influence the recruitment and evolution of plume-like features within the wedge (plug formation vs. entrainment)?
2. Do viscous remnants from plumes in the wedge lead to the evolution of two distinct upwelling zones, related to the plume tail versus the slab-plug interactions?

Figure 6: Laboratory and numerical models will be used to look at different aspects of plume-slab interaction on the melt production in a subduction system like that in the Pacific Northwest. Models (2-D: numerical & 3-D: lab) will characterize temporal and spatial (e.g., in 3-D, linear features versus focused features) patterns in circulation and melt production in response to 1) slab rollback in the presence of an RBL (rheological boundary layer) morphology expected for the High Lava Plains and 2) slab rollback with appropriate RBL scenarios in which a residual plug (in response to melting) evolves within the wedge. Finally, a third conceptual model will be tested involving the capture of a buoyant upwelling by wedge return flow (frames a and b). a) Illustrates the laboratory setup, making use of the existing subduction apparatus. New additions are overriding plates with various topographic shapes and a buoyant upwelling source. We will use peg 600 wax, which will begin to solidify at 15∞C within the upper surface boundary layer. We will test the conceptual model shown in (b) for producing the propagating volcanic tracks, where the High Lava Plains (HLP) side is produced by slab-driven upwelling and the Yellowstone side is fed by the buoyant tail. Laboratory models will document 3-D flow patterns and temperatures that will be used to calculate spatial and temporal patterns in melt production (e.g., previous lab. models show rapid evolution of a long, linear upwelling zone in the wedge [*Kincaid & Griffiths,* 2004]. Numerical models will explicitly calculate synthetic melts (distributions, volumes and compositions through time) [e.g., *Hall and Kincaid*, 2004].

To evaluate the effects of plume-slab interaction, we will test specific physical aspects of a plume-like feature entering the shallow mantle and the consequences of the flood basalt event leaving behind a large quantity of melt-depleted peridotite in the shallow mantle of eastern Oregon [e.g. *Humphreys et al.*, 2000]. Both laboratory and numerical models will be used to test how plumes might be captured into the wedge along sub-horizontal trajectories. 2-D numerical models will calculate the production and extraction of synthetic melts within these features.

These models will also characterize how the melted residuum (including melt effects on viscosity and buoyancy) interacts with the strong plate-driven return flow. Models will consider the spatial/temporal implications of melt production from continued flow through the plume tail - slab induced flow as these interact with the stalled and deforming residuum (Fig. 6). The 3-D aspects of these processes will be represented in the laboratory models using the existing apparatus and a plume of PEG wax that is buoyant and runny until it settles in the wedge, where its viscosity increases making it a plug-like feature. Detailed strain rate fields will be documented and imported to codes for computing 3-D splitting parameters [*Fouch et al.*, 2000; *Hall et al.*, 2000; *Lassak et al.*, 2004]. Detailed patterns in shallow vertical velocity (in plume vs. ambient fluid) will be incorporated into decompression melting models for producing synthetic melts. Models will test the conceptual model shown in figure 6 showing distinct melting regions evolving on either side of more viscous residual mantle.

3.2) *THE RELATION TO SUBDUCTION*

3.2.1) Imaging the Subducting Slab

Plume or no plume, the subduction system almost certainly has exerted influence over the composition, volume, and location of magmas erupting across this area. The magnitude of melt production during the flood basalt era clearly was greater than expected for simple stretching of continental lithosphere [*Arndt and Christensen*, 1992; *Gallagher and Hawkesworth*, 1992], particularly given the estimate of only 17% extension across eastern Oregon since 15 Ma [*Wells and Heller*, 1988]. *Carlson and Hart* [1987] suggested that the enhanced melting was caused not by a plume, but by directed flow of hot asthenospheric mantle into an opening mantle wedge beneath eastern Oregon as the previously shallow subducting Juan de Fuca plate increased its dip and retreated to the west. Since eastern Oregon is surrounded by Precambrian North America, which may have a thicker and more rigid lithospheric mantle than that beneath the young accreted crust of eastern Oregon, mantle flowing into the region vacated by the retreating Juan de Fuca slab would have to preferentially come from beneath the thick surrounding lithosphere instigating the rapid ascent of asthenospheric mantle into the opening void. A similar model of "edge effect" mantle flow to explain flood basalt volcanism was further explored by [*King and Anderson*, 1995, 1998] and the concept of enhanced mantle melting caused by flow around, or against, a retreating subducting slab has seen recent support [*Yogodzinski et al.*, 2001; *Kincaid and Griffiths*, 2003]. An interesting consequence of a slab roll back model is the expectation of an east to west progression of the volcanism (Fig. 7), like that seen in the migrating volcanism of the High Lava Plains.

Besides the possibility of a retreating slab in the Pacific Northwest, the southern end of the subducting plate, delineated by the Mendocino Fracture zone as it enters the trench, is moving north as a result of the strongly northeast oblique convergence. ***Does the southern edge of the subducting plate influence volcanism in the overlying crust as a result of edge-flow of mantle around the slab?*** As shown by results of geodynamic experiments on this issue (Fig. 7), edge-flow can cause focusing of mantle melting into a narrow band perpendicular to the trench. This could explain why the High Lava Plains magmatic trend is narrow in its N-S dimension rather than a broad band of migrating volcanism as expected for a simple slab retreat model without edge flow (e.g. Fig. 7b). At the time of the flood basalt episode 16 Myr ago, the southern edge of the slab should have been considerably to the south so that rapid slab rollback could instigate a N-S oriented line of volcanism in the Pacific Northwest similar to that observed in the dike system of the flood basalts.

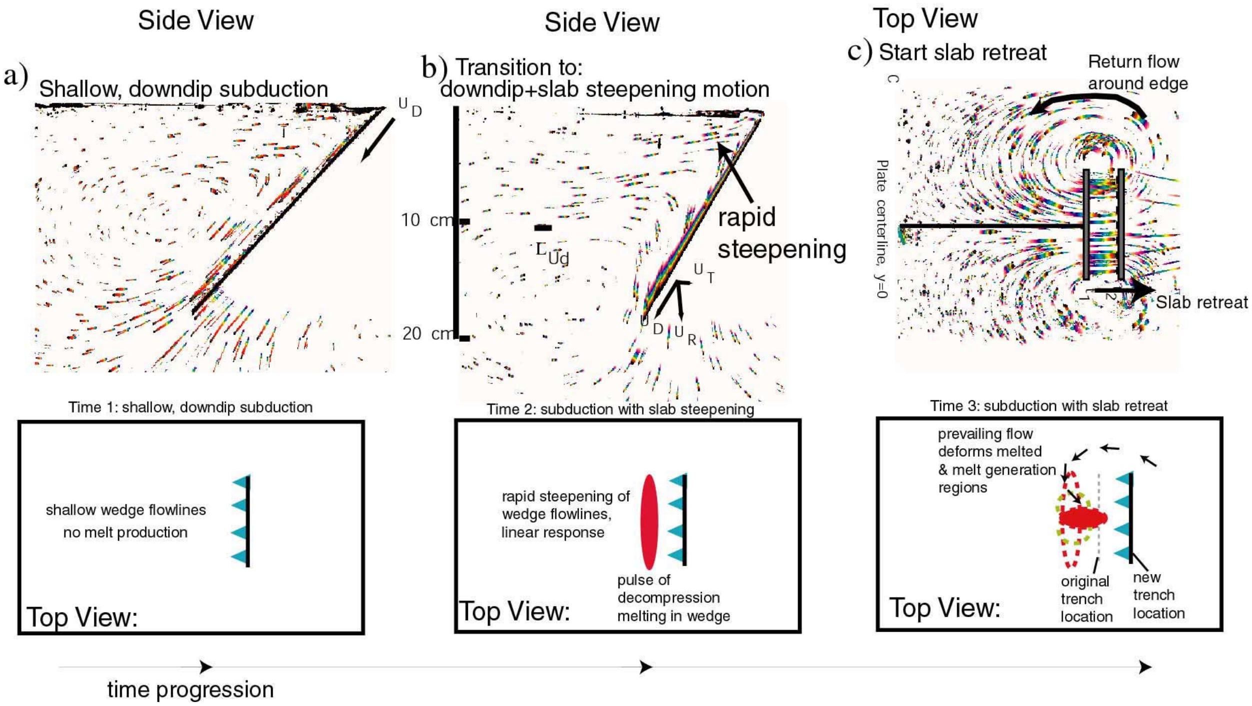


Figure 7: Combination of previous laboratory results (top row) with conceptual models for melt production (bottom row) within the wedge for a time evolution in subduction styles from a) shallow downdip motion of the slab to b) sudden onset of slab steepening to c) the initiation of slab retreat. In (a), flowlines in the wedge are shallow (nearly horizontal, unfavorable for decompression melting). In (b), the change in subduction mode produces rapid steepening of flowlines in the wedge and a long, linear pulse of decompression melting. In (c), the zone of residual melt (perhaps with increased viscosity) and the zones of active melting are deformed by the strong lateral return flow (or shear flow) to the wedge produced by slab retreat. This model will be tested in the proposed work by running similar subduction scenarios with added model aspects (variable topography for the base of the overriding plate; introduction of a increased viscosity region to represent the residuum). A 3-D network of gridded streak images will be analyzed with DPIV software to produce map-view slices of vertical fluid velocity from different depth horizons, for incorporation into melting models.

A major component of the proposed research on this subject is laboratory and numerical modeling of migrating and reorganizing subduction systems and the effects of the resulting mantle flow on mantle temperatures and subsequent volcanism. Figure 7 shows just one example from preliminary laboratory modeling of the effects of slab retreat, changing slab dip, and edge flow around the truncated slab. Laboratory models will build upon previous work to characterize 3-D aspects of circulation and thermal evolution of the shallow mantle in subduction zones [*Kincaid and Griffiths*, 2003, 2004]. Prior results show the strong influence of the style of plate sinking on the spatial and temporal evolution of the system. Slab steepening and slab rollback produce very striking horizontal and vertical patterns in flow in the wedge such as strong flow around the plate edge (Fig. 7c) and rapid increases in vertical velocity (Fig. 7b). Numerical models will also build upon aspects of two distinct sets of experiments. One set focuses on flow, temperatures and melt production in subduction zones with plate steepening and backarc spreading [*Kincaid and Hall*, 2003]. Other models have been developed to look at flow, temperatures and details of synthetic melts (volumes and compositions) in plume-ridge interaction models that include effects of dehydration and melting on viscosity and buoyancy of the residual mantle [*Hall and Kincaid*, 2003, 2004].

Finally, the idea that rapid and widespread melt production events may be produced due to slab rollback effects will be tested with both 3-D laboratory and 2-D numerical models. The laboratory models will run temporal sinking scenarios (as shown in Fig. 7) and will document details of flow patterns and temperatures in the shallow intraplate region of the wedge. Spatial maps of the vertical component of velocity will be produced over time and these results will be incorporated into decompression melting models (e.g. replacing the schematic frames in Fig. 7 with measurements) using the results of the experimental melting studies of the primitive basalts from the High Lava Plains. The spatial/temporal patterns in instantaneous strain fields will be incorporated into models of *Fouch et al.* [2000], *Hall et al.* [2000], and *Lassak et al.* [2004], to estimate mantle fabric (i.e. olivine lattice-preferred orientation) and predict shear-wave splitting parameters for direct comparison with the observed shear wave splitting from the seismic array (e.g. Fig. 5). Models will look specifically at the range of splitting patterns that may be produced given the rapid changes in strain fields that occur with sudden changes in slab sinking style.

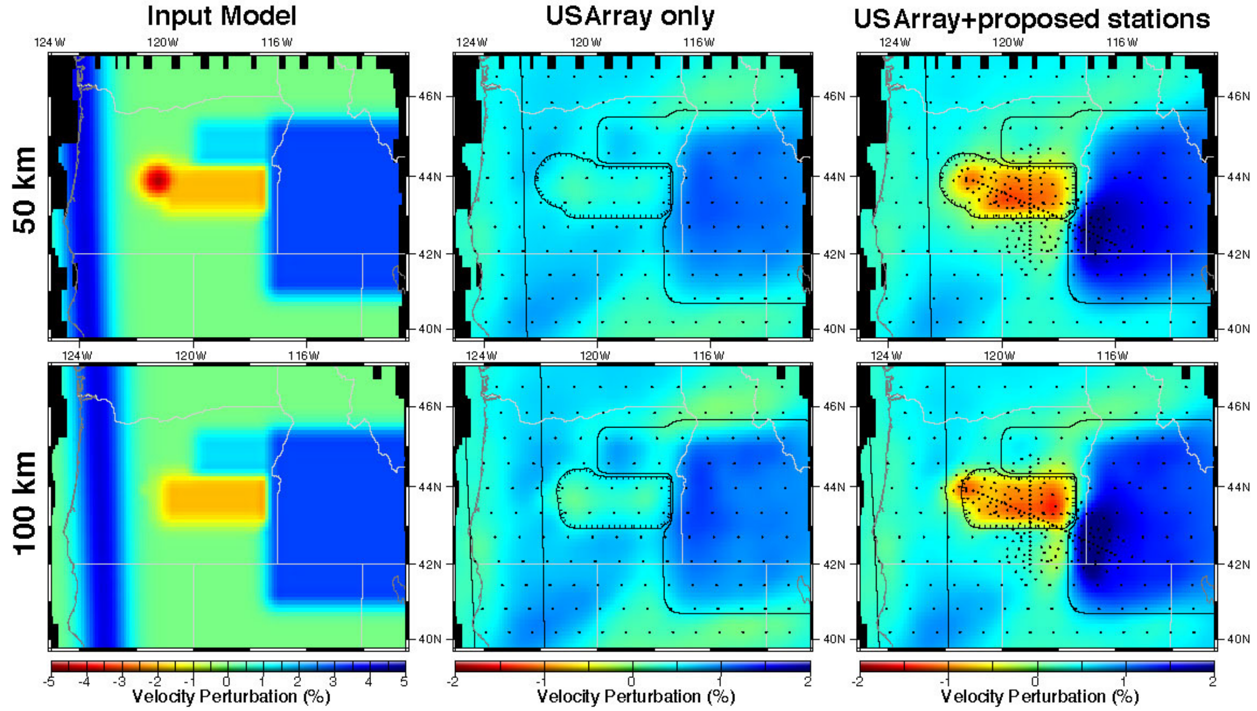


Figure 8: Horizontal cross-sections through hypothetical P-wave velocity models showing percent slowness velocity perturbations at 50 km (top 3 panels) and 100 km depth (bottom 3 panels). The resolution tests are based on an assumed two years of teleseismic events with body wave magnitude conservatively restricted to events ≥5.8. A relatively large P-wave rms noise level of 0.05s has been added to the synthetic data. Leftmost panels are map views of a starting model that includes: a hypothetical 2% low velocity tabular anomaly beneath the High Lava Plains region to a depth of 125 km; a 50 km diameter sphere of 5% negative anomaly beneath the Newberry region centered at a depth of 75 km; a Proterozoic North American lithosphere 3% faster than that of the surrounding upper mantle beneath central and eastern Oregon to a depth of 175 km; a hypothetical Blue Mountain lithosphere represented by a weakly positive anomaly of 1.5% to 125 km. In the western part of the region, a dipping 100 km slab with a tapered positive 4% velocity anomaly represents a descending plate at 45∫, but is not well imaged in these particular examples. We note that these features are for the purposes of illustration only and do not reflect any preconceived notion of velocity structure in the region.

Middle panels are the output models for linear inversions based on data from USArray Transportable stations alone (black dots; see also Fig. 2). Rightmost panels are the output models for linear inversions based on data from a combination of USArray stations and the additional densified arrays proposed for this study (black dots; see also

Fig. 2). These resolution tests clearly demonstrate that the proposed dense broadband array is critical for imaging structures in the upper 100 km of the mantle, where the smaller-scale distribution of thermal and chemical anomalies likely present in this region is directly applicable to the surface geology, petrology and geochemistry. Conversely, USArray stations alone provide little resolution of small features in the upper 100 km. The hypothetical boundary with Proterozoic North America is best defined where the NW-SE densified swath of stations crosses near the Oregon-Idaho border. These examples demonstrate a characteristic problem with tomographic models where velocity anomalies tend to ìsmear outî with depth, demonstrating the need to combine tomography with receiver function imaging and array-based processing techniques to map discontinuities precisely. The tomography does an extremely good job, however, of imaging the geographic boundaries and horizontal extent of the anomalous bodies, which will be further enhanced by the nonlinear inversions that will be performed on the real data.

Assessing the role of edge flow depends both on detecting the deep slab itself (not yet done in this region) and then determining if the slab edge lies beneath the region of study. The Juan de Fuca slab east of the Cascades has to date been a remarkably elusive feature to image seismically. One of the principal design goals of the proposed research is to image both the slab itself, including its southern boundary, and the 3-D velocity (and, by inference, temperature) structure of the mantle wedge above the descending plate. The tight station spacing (20-30 km) of the broadband array (see Fig. 2 and caption) assures sufficient ray crossing at shallow depths to enable tomographic imaging of features up to the uppermost mantle and even into the lowermost crust. This enhanced resolution is a critical component for mapping both zones of partial melt in the uppermost mantle and lowermost crust and possible plugs of residual material in the uppermost mantle beneath the zone of volcanism. The dense array itself is of sufficient extent (500x350 km) that we will have good resolution to depths of at least 300-400 km. For greater depths, the Bigfoot array will provide essential data but at lower resolution. We note that a critical component of this part of the project is to have sufficient resolution to be able to correlate features observed in the mantle with the volcanic record in the overlying crust. Of particular importance will be zones of partial melt and/or high temperatures that are likely to be confined to restricted areas in the uppermost mantle. The resolution tests shown in Figure 8 confirm both the need for high array density to image these critical features in the uppermost mantle and the limited ability of the Bigfoot deployment to do so.

3.2.2) Detecting a Slab Contribution in the Magmatism

Like the ignimbrite sweep before it, the temporally migrating volcanism on the High Lava Plains is not of the composition expected for convergent margin volcanism. If this volcanism is related to the subducting plate, is the relationship direct, for example through flux-melting induced by water-rich fluids rising from the downgoing plate, or indirect though induced flow in the mantle to replace the area previously occupied by the retreating slab (Fig. 7b)? We suggest that the ideal place to address the role of subduction in slab-roll back volcanism is Newberry Volcano. Newberry is the current locus of the migrating High Lava Plains trace and is an area of anomalously voluminous, and compositionally variable, recent volcanism on the eastern side of the Cascade volcanic front. Newberry currently is being mapped in detail by Dr. Julie Donnelly-Nolan of the USGS. At no cost to this proposal, Dr. Donnelly-Nolan has offered to collaborate with us in using Newberry to test the role, if any, of Juan de Fuca subduction in instigating this volcanism. Dr. Donnelly-Nolan's detailed mapping, geochronology and geochemistry in the Newberry area will allow us to select appropriate samples for additional study to investigate whether or not subduction related fluids/melts are a component of the source of these magmas. To address this issue, we will add to Dr. Donnelly-Nolan's geochemical results data for isotopic systems that have proven their use in detecting slab-contributions, particularly boron [*Leeman*, 1996] and lead that can be used in concert with Sr and Nd isotopic data to evaluate whether or not fluids/melts from subducted sediment or oceanic crust contributed to the source of these magmas. Boron isotopic compositions will be determined by laser ablation ICP-MS following the methods developed at DTM [*Le Roux et al.*, 2004]. We also will determine the volatile contents of melt inclusions (when they can be found) contained in olivine in primitive basalt lavas from Newberry using the ion-probe techniques described by *Hauri et al.* [2002] that measure H, C, S, F and Cl concentrations. This geochemical work will be done by PI Carlson at DTM.

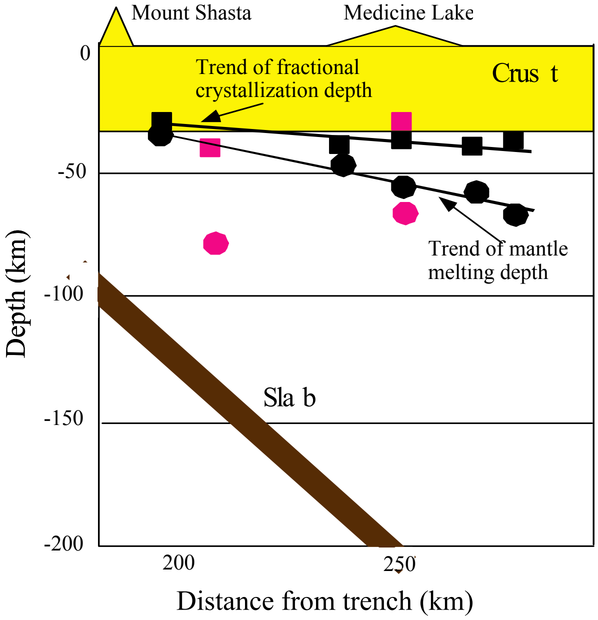


Figure 9: Schematic cross-section across the Cascade arc to the south of High Lava Plains study area showing petrologic estimates of depth of mantle melting and crustal fractionation. The position of the slab and the thickness of the crust are inferred from geophysical evidence. Squares show maximum depth of fractional crystallization of olivine and plagioclase and circles show mantle melting depth. Temperature of mantle melting also varies systematically across the arc from 1300 °C in the east to 1450 °C in the west. Two vents, Tennant and Yellowjacket, fall off the trend, because these lavas were modified by the addition of a slab fluid.

Dr. Donnelly-Nolan's ongoing investigation at Newberry volcano has identified the existence of several primitive basalt magma types. Some examples of these basalts are given in Table 2. Basalts similar to these are least modified by fractional crystallization at crustal pressures and therefore are best representatives of mantle melt compositions and also the best starting compositions for developing models of crystallization of more evolved magmas at crustal and upper mantle depths. Compositions will be chosen that are the most important for calibrating the depth and temperature conditions that led to melt generation in the mantle.

Table 2: Compositions of primitive lavas from Newberry(N) volcano to be subjected to experimental study and comparison with lavas from Medicine Lake (ML) volcano. Chemical analyses are courtesy of Dr. Julie Donnelly-Nolan and *Bartels et al.* [1991].

Sample	#	SiO_2	TiO2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mg#	Sr	Ba
HAOT	51Jc	49.4	0.68	18.1	7.77	9.65	11.78	2.06	0.28	0.25	0.69	148	115
Alk bas	222J	50.1	1.15	16.1	7.74	9.58	10.61	2.88	1.15	0.46	0.69	1060	880
Alk bas	367J	49.0	1.43	17.2	8.96	9.58	10.10	2.85	0.50	0.27	0.65	391	155
Bas and	753J	52.2	0.92	17.2	7.39	8.61	9.04	3.02	0.63	0.21	0.67	525	228
ML-HAOT	82-72c	47.8	0.59	18.3	7.5	10.4	12.1	2.88	0.03	0.03	0.7	187	40

Note that one of the basalts (51Jc) is very similar in composition to HAOT lavas that have been investigated experimentally [*Bartels et al*, 1991] and melting conditions for these lavas can be predicted using the methods outlined in *Elkins-Tanton et al.* [2001]. However, other primitive basalts (222J and 367J) are distinctive in containing much higher abundances of K_2O, P_2O_5, and TiO_2 and also higher FeO contents. A primitive basaltic andesite (753J) resembles high H_2O, primitive arc magmas that are found in the southern Cascades [*Bacon et al.*, 1997; *Grove et al.*, 2002]. The nature of the arc contributions to the Newberry system will be investigated through experiments on 753J and other primitive lavas that we anticipate we will find as Dr. Donnelly-Nolanís mapping continues. As discussed in the next section, new experimental studies are necessary to define the temperature and depth of melting for the high K_2O basalts that are represented at Newberry and in the eastern end of the study area.

The results of these experiments will be used to develop models of the dependence of basalt compositions on temperature, pressure and H_2O content. These models will be applied to the basalts that cover the study area. In parallel with the experimental studies, it will be necessary to characterize mineral compositions in several of these basalts to provide information necessary for estimating pre-eruptive H_2O content. The samples chosen for the mineral chemistry analyses also will be the focus of the melt-inclusion analyses described above. The proposed high-pressure experiments on Newberry lavas will strengthen and extend the predictive models of *Kinzler* [1997], *Kinzler and Grove* [1992] and *Gaetani and Grove* [1998] to allow calculation of pressure, temperature volatile contents and melting conditions of basaltic lavas across the High Lava Plains. The techniques developed by *Elkins-Tanton et al.* [2001] will be applied to the study area to estimate the depth ñ temperature conditions for fractional crystallization and mantle melting in order to produce a snapshot of mantle melt defined temperature ñ depth ñ melting extent field in the mantle beneath Newberry and extending into the High Lava Plains in an analogous manner to that shown in figure 9.

3.3) THE ROLE OF LITHOSPHERIC STRUCTURE

Various characteristics of lithospheric structure such as degree of extension, crustal thickness, and the presence or absence of thick lithospheric mantle, often are invoked as controlling factors in continental volcanism. In the Pacific Northwest, the flood basalts were erupted from a N-S oriented dike system paralleling the 0.706 line, indicating that this magmatic episode exploited this old lithospheric suture even if the mantle melting was instigated by a plume. The continuing volcanism in both the High Lava Plains and Snake River Plain are occurring near the northern terminus of Basin and Range extension. At least for the High Lava Plains, volcanism has been concentrated along the Brothers Fault zone, one of the major fault systems in this area. Even the Quaternary volcanism in this area appears to be localized to two of the terrane boundaries, Newberry Volcano at the interface with the Cascades, and on the eastern margin of the High Lava Plains from Diamond Craters to the Jordan Valley volcanic field (Fig. 3) that straddles the 0.706 line.

We have already outlined our plans for investigating subduction influence at Newberry (section 3.2.2), and we here suggest that examination of primitive basalts from the eastern margin of the High Lava Plains as it transits into Proterozoic North America provides an ideal opportunity to use the young volcanism in both areas as tests for lithospheric influence on magma generation and eruption. Some recent models indicate that only slices of accreted oceanic crust and oceanic asthenospheric mantle lie to the west of this boundary in eastern Oregon [*Evans et al.*, 2002]. With the active seismic experiment in this project, we will measure both Moho depth and crustal velocities across this boundary. These data will be coupled with receiver function analysis of Moho depth and high-resolution broadband array tomographic measurements of changes in lithospheric thickness across the boundary of the High Lava Plains and Proterozoic North America. Across this boundary, we have the expectation of transiting from thin accreted oceanic lithosphere with a thin to non-existent lithospheric mantle to Proterozoic continent with thick felsic crust and thicker lithospheric mantle. Given the perturbation to these boundaries caused by the extensive Cenozoic magmatism in this area, this image of the lithospheric boundary may well be overly simplistic, but almost any result from the imaging will provide important input to evaluate the causes of the compositional heterogeneity of volcanism near this boundary and whether or not lithospheric structure has played a role.

3.3.1) Compositional Indications for Changing Source Materials and Melting Depths

What we already know about this boundary is that the compositional and isotopic characteristics of the young primitive basalts change dramatically across this area (Fig. 4, Table 3). Approaching the Jordan Valley volcanic field and the 0.706 line, the primitive high-Al olivine tholeiites (HAOT) found to the west change in isotopic composition and increase in compositional diversity adding high TiO_2, FeO, K_2O and P_2O_5 compositions similar to those that dominate the basaltic volcanism on the Snake River Plain [*Hart,* 1985; *Leeman et al.*, 1992; *Shoemaker and Hart*, 2003]. The increasing Fe concentration of most basalts east of the 0.706 line could suggest deeper melting, although the much higher Ti contents and variable isotopic compositions of these lavas also imply compositionally distinct sources in the continental lithospheric mantle. In addition, the Jordan Valley volcanic field contains the only example of mildly alkaline basaltic volcanism (for example, sample 86-2 in Table 3) in this portion of SE Oregon with chemical compositions more similar to Tertiary basalt of the central Basin and Range (e.g. *Fitton et al.* [1988]) and isotopic characteristics more akin to basalts erupted from farther west along the High Lava Plains (*Hart*, 1985; *Bondre and Hart*, 2004).

Table 3: Compositions of young (< 11 Ma) primitive lavas from east of Steens Mtn.

Sample	#	Age	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mg#	$^{87}Sr/^{86}Sr$
ALK	86-2	<0.01	47.35	2.17	15.90	10.74	9.46	9.84	2.86	0.69	0.30	0.61	0.7038
HAOT	8-75A	0.4	48.68	0.88	16.43	10.07	9.25	11.51	2.50	0.28	0.13	0.62	0.7046
TRANS	9-29	0.4	47.08	1.80	16.16	10.51	9.08	11.00	2.54	0.50	0.23	0.61	0.7048
HAOT	96-8D	0.6	46.92	0.92	15.79	9.82	9.62	11.71	2.40	0.16	0.20	0.64	0.7053
HAOT	92-1	0.5	47.52	0.99	15.92	9.70	10.95	11.65	1.91	0.11	0.08	0.67	0.7065
HAOT	9-27	5.0	47.71	0.81	16.54	10.19	9.22	12.19	2.29	0.11	0.11	0.62	0.7059
HAOT	9-6A	5.1	46.75	1.19	16.54	10.47	9.76	11.31	2.20	0.17	0.21	0.62	0.7062
TRANS	8-69F	8.5	47.19	1.92	15.31	12.04	9.29	10.28	2.25	0.41	0.54	0.58	0.7066
HAOT	5-12A	8.5	47.65	1.25	16.26	9.80	9.89	11.49	2.28	0.34	0.15	0.64	0.7068

Rock type abbreviations include HAOT - high Al olivine tholeiite; TRANS - tholeiites transitional between HAOT- and Snake River olivine tholeiites; ALK - mildly alkaline olivine basalt. Ages given in millions of years. Data from *Hart* [1985], *Hart et al.* [1997]; *Shoemaker and Hart* [2003]; *Hart* [unpublished].

Experimental studies on low-K basaltic compositions (HAOT from Medicine Lake volcano, CA [*Bartels et al.*, 1991] and MORBs [*Kinzler and Grove*, 1992; *Grove et al.*, 1993; *Ghiorso and Sack*, 1995; *Kinzler*, 1997] have been used to develop predictive models for the pressure and temperature of the segregation of a melt from its source region [Fig. 9, *Elkins-Tanton et al.*, 2001]. These models have been very successful in predicting crystallization/melting conditions within the range of pressure, temperature and bulk compositions for which they are calibrated, but our experience shows that they do a poor job of prediction outside the compositional range of calibration. This is true for both empirical models and thermodynamically based models, where temperature estimates can be in error by as much as 150 °C [*Gaetani et al.*, 1998, *Parman and Grove*, 2004]. In particular, K_2O, P_2O_5, and TiO_2, minor constituents in basalts that vary widely in concentration in the basalts of eastern Oregon, have large and as yet poorly understood influences on predicted temperature and pressure. As much as 350 °C per 0.1 wt % change in K_2O is predicted by *Kinzler* [1997], but the range of compositions spanned by their calibration experimental data set is 0.03 to 0.10 wt. % K_2O. These are clearly unrealistic influences and experimental data that extend the compositional range are required to improve predictive capabilities here and for lavas at Newberry volcano.

The melting experiments on lavas from the eastern end of the High Lava Plains and from Newberry will be carried out using the piston cylinder under anhydrous and H_2O-bearing conditions using techniques pioneered in the MIT laboratory [e.g. *Bartels et al.*, 1991; *Kinzler and Grove,* 1992; *Baker et al.,* 1994; *Kinzler,* 1997; *Gaetani and Grove,* 1998]. As with the work described in section 3.2.2 for Newberry, the samples selected for experimental work will be fully characterized geochemically. Many of these rocks have seen previous geochemical study [*Hart et al.*, 1984], but a good portion of this work was done in the early 1980's when the only compositional analytical technique available to us was XRF. As a result, many of these basalts have only minimal trace element concentration data, though most have already been analyzed for O, Sr, Nd and Pb isotopic composition [*Hart,* 1985]. For the select set of primitive basalts chosen for additional study on the basis of their major element composition, we will fill in the missing data, obtaining full trace element compositions by ICP-MS, boron isotopic compositions by laser-ablation ICP-MS, and compositional information on their constituent minerals and, where available [e.g. Johnson et al., 1996], melt inclusions, using both the electron and ion microprobes. These data will be particularly valuable to compare with the similar dataset to be obtained from the western end of the High Lava Plains trace near Newberry in order to evaluate the influence of these very different tectonic settings on the depth and temperature of melting and whether or not slab fluids and/or the lithospheric mantle play an important role in determining the compositional features of the volcanism.

3.4) *CRUSTAL INFLUENCE ON, AND RESPONSE TO, CONTINENTAL VOLCANISM*

The previous section was concerned primarily with comparing mantle seismic imaging with geochemical and petrologic results for primitive basalts used as tracers of the conditions of mantle melting and how they are affected by lithospheric boundaries in the mantle. The crust - its thickness, composition, temperature, and structural integrity - also can exert control over the composition, eruptive volume, and location of continental volcanism. Eastern Oregon provides an ideal natural laboratory to investigate not only how crustal characteristics can influence volcanism, but also how extensive magmatism can modify crustal characteristics. In order to investigate these issues, we will:

- Examine the relation of extension and magmatism by determining crustal velocity and density profiles from the unextended and amagmatic Blue Mountains across three volcanic centers respectively erupted through the extremely magmatically active, but minimally extended, northern High Lava Plains; the axis of flood basalt magmatism at the large Basin and Range fault that forms Steens Mountain; and the more highly extended, but less magmatically active, Basin and Range in southern Oregon and northern Nevada

- Examine how the composition of the crust has changed with time in response to the magmatism as reflected in the composition of crustal melts erupted at various times over the last 17 Ma in the High Lava Plains
- Compare the thickness, velocity, and density of the crust as measured by seismic refraction and gravity data with estimates of volcanic volumes erupted and intruded into the High Lava Plains over the last 17 Ma in order to evaluate the magnitude of magmatic reworking and addition to this crustal section

3.4.1) Seismic Determinations of Crustal Structure

The crustal refraction studies involve a total of 14 shots of one to two tons each that will be fired at intervals of ~60 km along the two profiles shown in Fig. 2. We will also record large mine blasts from the GoldStrike mine in northern Nevada (Fig. 2), which *Louie et al.* [2004] have shown are large enough to constrain deep lithospheric structure. We will deploy a minimum of 840 stations along the two cross-profiles at once and record all shots at all receivers, and approach that will provide substantial 3-D coverage. The N-S refraction profile ties to an east-west profile across NW Nevada just south of the Oregon border shot by the Stanford geophysics group in September of 2004, and the NW-SE profile links at Newberry with the refraction survey of *Catchings and Mooney* [1988] and *Achauer et al.* [1988] (Fig. 2).

The active source data will provide detailed crustal and uppermost mantle control (primarily of Vp) along refraction profiles. These data will be coupled with passive source data to obtain Vs, extrapolate between and beyond these profiles, and probe the upper mantle. Techniques for this are still being refined, but we have successfully used drill hole data in a way that emulates what we plan to do for receiver functions in a joint inversion with refraction data in recent experiments [e.g. *Averill et al.,* 2004]. We plan to treat the point where the teleseismic wave intersects the Moho a pseudo-shotpoint so that its arrival at the surface can be jointly modeling in 2-D or 3-D using currently available inversion codes [*Hole*, 1992; *Zelt and Smith*, 1992]. Similarly, we can use the two data sets, including wide-angle reflections, to calculate both Vs and the Vp/Vs ratio.

Gravity data will be used as a further constraint on upper crustal structure and a matching 3-D gravity model will be constructed. The UTEP group has both in-house and commercial 3-D gravity modeling packages. The Carnegie group has extensive experience integrating seismic and gravity results [*Webb et al.,* 1999, 2004]. The modeling will enhance prospects for an integrated analysis with the geological, geochemical and petrological studies.

Of additional importance in the integrated approach is the analysis of lithospheric mantle reflectors. Improved instrumentation has made it possible in refraction experiments to image reflecting horizons below the Moho [e.g., *Keller et al.*, 1994; *Grad et al.*, 2002; *Gorman et al.*, 2002; *Keller et al.*, 2003]. These features tend to be discontinuous and poorly correlated between shots, making them prime targets for integrated controlled source and teleseismic data.

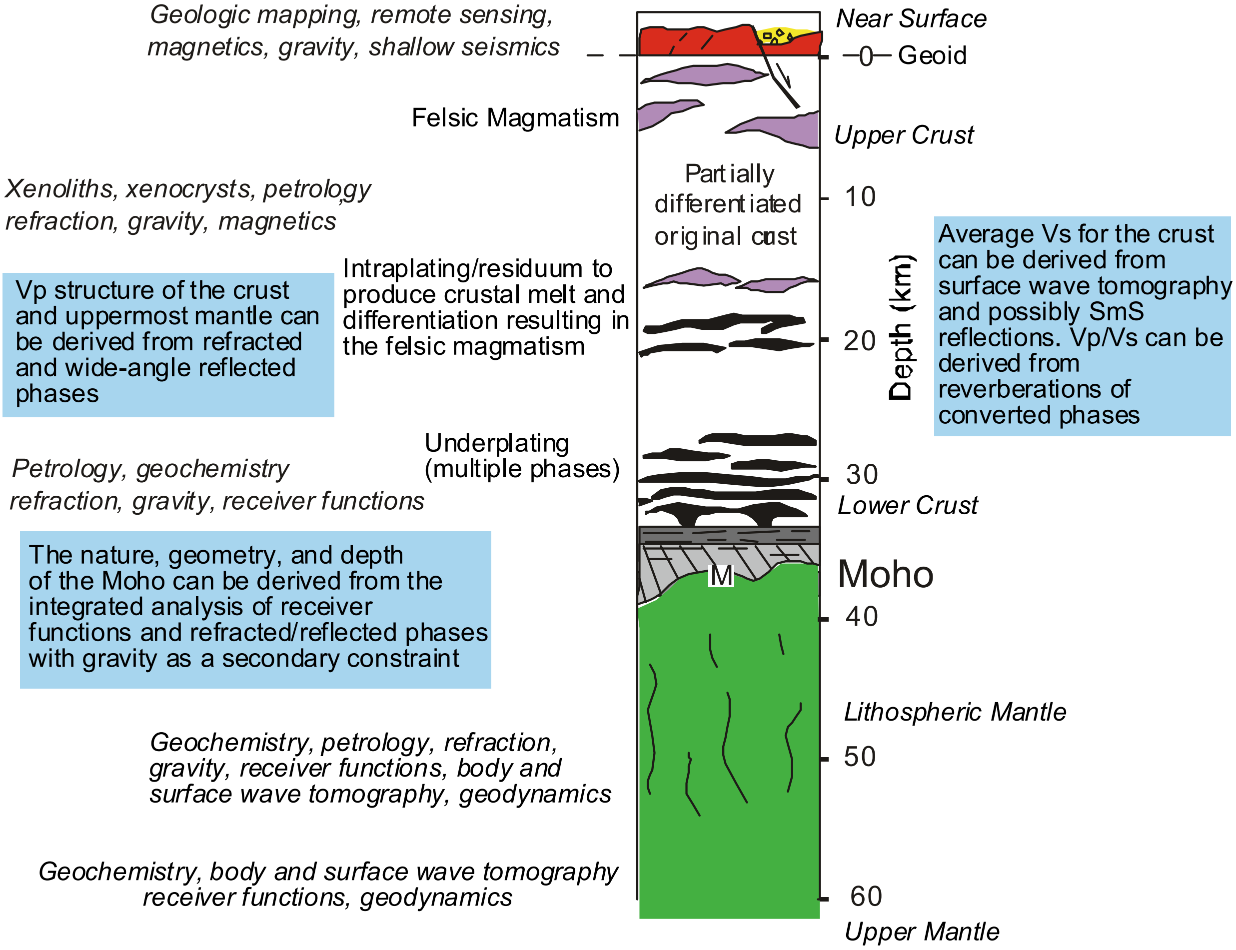


Figure 10: Schematic showing the strategy for multidisciplinary imaging of the crust and upper mantle.

3.4.2) Relation of Magmatism to Faulting and Extension

By starting the N-S oriented seismic deployment in the Blue Mountains, we will obtain an image of crustal velocity and density structure in the accreted lithosphere that has not been subjected to intense Cenozoic magmatism or extension. This will provide a "baseline" structural image for this crust that can be compared directly with a nearby area in the High Lava Plains that experienced one of the largest volcanic events in the area, the eruption of the Devine Canyon Tuff (Fig. 3, *Walker*, [1970]). The Devine Canyon Tuff covers a fair fraction of the High Lava Plains and presumably was erupted from the Harney Basin (Fig. 3), which will be crossed by the seismic deployment. Seismic imaging will continue south of the Harney Basin across the western flanks of Steens Mountain - the eruptive site of some 65,000 km^3 of basalt during the flood basalt episode [*Carlson and Hart*, 1987] and then across another silicic center - the Hawkes Valley complex (Fig. 3) - before crossing into northern Nevada and the reappearance of older basement exposed in Basin and Range uplifts as Mesozoic igneous intrusions into Paleozoic sediments.

Comparing the Devine Canyon, Steens Mountain, and Hawkes Valley crustal sections is of particular interest in evaluating the role played by the crust as both a source of magmas and a controlling factor in whether mantle-derived magmas erupt or pond within the crust. Both silicic centers occur along the right-lateral fault systems of the High Lava Plains (Devine Canyon along the Brothers and Hawkes Valley along the Eugene-Denio fault systems, Fig. 1), and the Steens Mountain feeder dikes are exposed in one of the most spectacular Basin and Range faults in eastern Oregon (Fig. 3). The huge caldera source of the Devine Canyon eruption and the large volume Steens eruptions occurred purely in the accreted terranes whereas the comparatively small silicic dome field of Hawkes Valley is near the boundary between the accreted terranes and the Precambrian crust of northern Nevada. In spite of erupting through much more highly extended crust, the Hawkes Valley field contains but a small fraction of the eruptive volume of the Devine Canyon center, formed at the northern boundary of the High Lava Plains where extension was minimal. By comparing lithospheric structure to be obtained by the seismic and gravity surveys, we hope to evaluate whether the very distinct volcanic styles and volcanic volumes in these three centers relate to crustal structure or whether the larger volumes erupted at Devine Canyon and Steens require a much more significant contribution from hot underlying mantle as might be expected in the plume outflow models.

3.4.3) Compositional evolution of the High Lava Plains crust

The pervasive volcanic and sedimentary cover of the High Lava Plains precludes direct sampling of the crust. Based on basement exposures of the oceanic and arc terranes in the Klamath Mountains to the southwest and in the Blue Mountains to the north, such lithologies are thought to underlie much the High Lava Plains, but in order to investigate how the crust has been modified by the Cenozoic magmatism, this assumption needs to be evaluated. We will pursue two direct sampling approaches of the sub-volcanic basement. First, we will collect and analyze for their compositional and isotopic (O, Sr, Nd, Pb) character sparse crustal xenoliths that have been erupted by explosive silicic volcanism. The samples presently available are hornfels-facies metasandstones [*Streck*, 2001]. Such sampling will give some insight into the upper crust, where the magma that entrained the xenoliths resided, but we know of no xenoliths from deeper sources. A second, and less direct, method of sampling the crust is to date, by the U-Pb method, zircon grains entrained in peraluminous to metaluminous silicic volcanic rocks. Because such compositions have a substantial crustal component in the magma, and because the magma is likely to be zircon saturated throughout its history, the zircons are typically complexly zoned and carry a record of their crustal sources. We intend to separate zircons from a suite of silicic volcanic rocks already collected by Grunder, Hart, and Carlson that span the space and age distribution of much of the High Lava Plains. Additional samples will be collected, as appropriate, along the planned geophysical transects. These zircons will be analyzed by in-situ laser ablation ICP-MS at the Carnegie Institution, or at Oregon State University as analytical techniques are expanded there.

The composition and isotopic character of silicic volcanic rocks that are of crustal origin can themselves be used as probes of the crust. Addition of targeted isotopic analyses of samples spanning the age-space-compositional spectrum, particularly of centers targeted in the geophysical surveys like Devine Canyon and Hawkes Valley, will allow reconstruction of likely crustal reservoirs, how they vary in time and space, and how the silicic volcanic rocks compare to the basaltic rocks. Analyses will include bulk rock O, Sr, Nd, and Pb isotopic characterization as well as Pb isotopic composition of feldspars by in-situ laser ablation ICP-MS analysis. Such analyses for plagioclase are being successfully conducted at Oregon State; alkali feldspar is also common in rhyolites of the High Lava Plains and their high Pb concentrations lend themselves to in-situ analysis. Like zircons, feldspar may retain isotopic domains that yield clues to protracted crustal magmatic history. Sparse existing (bulk) isotopic data indicate that Middle Miocene volcanic rocks are rhyolites and rhyodacites with more ìcrustalî (greater $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$) signatures than the Late Miocene to Recent (westward-younging) high-silica rhyolites that isotopically mimic coexisting mafic volcanic rocks [*Streck et al.,* 1999; *Jordan,* 2004]. Rare earth element patterns of the younger rhyolites are, in some cases, lower than ambient mafic rocks and additionally are depleted in the middle rare earth elements indicating an origin by partial melting of amphibolite [*Maclean*, 1994; *Streck et al.,* 1999]. This implies that the silicic volcanism of the Late-Miocene to Recent age-progressive suite sampled a crust that had been substantially modified by mafic magma injection, or that the depth of crustal magmatism changed with time. Comparison of crustal melts in one place, but through time, will be important to interpreting images of the crust (Fig. 10). Based on the extant data on silicic volcanic rocks [e.g., *Walker, 1974; Rytuba and McKee*, 1984; *Linneman and Myers*, 1990; *Draper*, 1991; *Streck and Grunder*, 1995, 1997; *Johnson and Grunder*, 2000], and the abundance of basaltic volcanism, we anticipate that the crust of High Lava Plains may be substantially modified by mafic intra- or underplating.

3.4.4) Structural Evolution of the High Lava Plains Crust in Response to Magmatism

Along the basalt-covered Snake River Plain, a thick layer of solidified basaltic magma is inferred to exist in the middle to deep crust based on seismic imaging [*Peng and Humphreys*, 1998], low topography, a strong positive isostatic gravity anomaly (Fig. 3), and the thermal budget required to drive the extensive crustal melting that gave rise to the vast rhyolites of the Snake River Plain [*McCurry et al., 2002*]. Subdued topography, abundant silicic volcanic rocks and differentiated mafic volcanic rocks all suggest a substantial amount of mafic injection into the crust of the High Lava Plains. How deep? How much? and When? are the questions that will be addressed by petrologic modeling and seismic imaging of the crust to be undertaken in this project. Does the lack of a positive gravity anomaly throughout the volcanic terrane of eastern Oregon (Fig. 3) imply that mafic underplating has not taken place, or has the crust compensated for these additions by thinning through more extension than is predicted by paleomagnetic evidence for rotation of the Oregon coast ranges [*Wells and Heller*, 1988]? Are the mafic crustal rocks compensated by a low-density residuum in the uppermost mantle? Before the emergence of PASSCAL instrumentation, a modest (by todayís standards) refraction experiment showed evidence of a relatively thick (~10 km) 7.4 km/sec layer, interpreted by *Catchings and Mooney* [1988] to be mafic underplating at the base of the crust east of Newberry Volcano. These layers are hard to detect without dense recordings and their extent relative to surface features is a crucial issue targeted by this study. The proposed seismic refraction profiles will feature a station spacing of ~700m with shots spaced at ~60 km. This recording geometry will insure that the resolution in the lower crust is sufficient to determine its velocity structure. The long profiles extending from the Goldstrike mine in Nevada will help determine the extent of lower crust features as will the integration with the teleseismic array results.

The volume of basalt that has been delivered from the mantle to the crust also can be constrained from the volcanic record. The direct signal is the volume of basalt erupted at the surface. We will compile and improve space-time-volume distributions of silicic and mafic volcanic rocks in the High Lava Plains through a combination of selected geochronological studies coupled with GIS-based volume calculations currently being done for Colorado volcanism by Lang Farmer using the NAVDAT database. With the exception of the recent *Jordan et al.* [2004] work, much of the geochronology done in this area is whole rock K-Ar dating carried out in the 1970's and 1980's that suffers in both precision and accuracy in comparison to modern Ar-Ar age dating. The erupted volume, however, is only a minimum amount as additional volumes of basalt may stall in the crust where they differentiate to make more evolved mafic magmas as well as provide thermal energy for crustal melting [e.g., *Huppert and Sparks*, 1988; *Hildreth*, 1981, *Grunder*, 1995]. Stalling of basalt under low-density silicic systems is an effective way of driving differentiation in both and of stratifying the crust (e.g. Fig. 10). Existing petrologic modeling of non-primitive basalts of the High Lava Plains suggests that substantial differentiation, mainly by crystal fractionation, took place at middle crustal depths with moderately low water concentrations to enhance clinopyroxene versus plagioclase crystallization [*Carlson and Hart,* 1987; *Streck and Grunder*, 1999; *Jordan*, 2004]. If young rhyolites are partial melts of mafic intraplated crust and are thermally sustained by mafic crustal intraplating, then large volumes of gabbroic and ultramafic cumulate rocks ought to exist in the mid-crust of the High Lava Plains (Fig. 10). Comparison of the High Lava Plains crust to that of the Blue Mountains will provide a test of how much intra- or under-plating. Modeling the time-space record of volcanism will constrain how and when the present crustal structure developed.

4) Work Plan and PI Responsibilities

Throughout the proposal we have identified the tasks to be undertaken by individual PIs in connection with the scientific questions, or analytical approaches, being pursued. Here we explicitly summarize the roles of each PI, plans for the most efficient shared utilization of the facilities under the direction of individual PIs, and how we anticipate integrating these efforts.

The staging area for seismic operations is provisionally located on the OSU campus in Bend, Oregon and PI Hart has received verbal permission from the Skinner Ranch in Jordan Valley, Oregon to utilize space on their property for additional seismic staging activities. Up to 30 broadband instruments will be available from the Carnegie and ASU seismometer pools, and the remainder will be requested from PASSCAL. We expect the usual 2-year wait for PASSCAL broadband seismic instrumentation; nonetheless, site surveys and permitting for both the broadband and active components of the seismic experiment will begin as a follow-up to the first group workshop, currently scheduled for the end of summer 2005. Randy Keller and chief UTEP experiment coordinator Steve Harder have already performed a detailed logistical assessment of requirements for the active source experiment. Fine-tuning of this effort will be achieved in the field with the guidance of Hart, Grunder and Carlson. All PI's of this proposal will participate in the refraction/low-fold reflection surveys, as will the usual army of students engaged in instrument deployment during the actual 2 weeks of shooting. The scheduling of the active source experiment will be coordinated with the broadband deployments to assure maximum data recovery, but it is currently planned for early summer, 2007 (Fig. 11). Keller will have primary responsibility for producing crustal and uppermost mantle images across the two active source lines in the array and integrating the gravity and magnetic data into the analysis. Keller will supervise one graduate student through the course of the project and funds are requested for an additional graduate student position in the year the active experiment is conducted.

David James and Matt Fouch and their support personnel will assume joint responsibility for permitting, deployment, and operation of the broadband stations and for timely data archiving at the IRIS DMC. The ASU group is currently funded by IRIS and USArray to provide next-generation siting reconnaissance tools (i.e., logistics, contacts, GIS-driven databases, etc.) for use during the entire 12-year USArray deployment. These tools will be leveraged to provide essential assistance in siting and permitting the large number of stations proposed here. Participants in those efforts will include Carnegie seismology technician Peter Burkett as well as at least one CIW postdoc and several ASU and UTEP undergraduate and graduate students. Fouch will lead the anisotropy imaging, and Fouch and James will co-lead the tomography and discontinuity imaging. PI Fouch is currently collaborating with S. Rondenay (MIT) in scattered energy imaging for a tightly spaced array near Kimberley, South Africa. These receiver function migration tools will be applied to discontinuity imaging in this study.

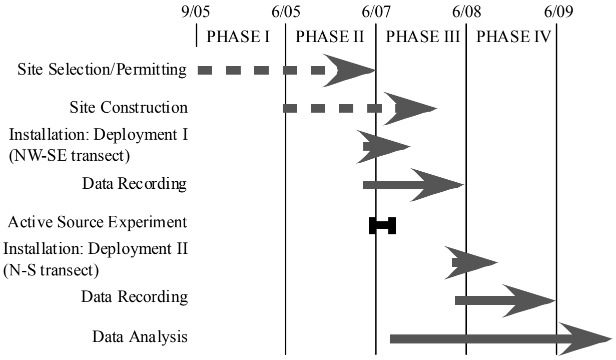


Figure 11: Project timeline for the active source and broadband deployments. Deployment I covers the NW-SE transect and includes the 32 station telemetered profile and 60 stations of the densified array (Fig. 2). Deployment II is the N-S transect and includes the redeployment of 20 stations of the telemetered array and approximately 40 stations of the densified array. This timeline reflects the expected 2-year wait for PASSCAL instrumentation.

The multiple datasets from this experiment, both active source and broadband, will support several M.S. and Ph.D. theses, as well as several undergraduate research projects. The broadband analyses will be closely integrated with the active source studies by Keller and his students and with the geochemical and petrological studies related to defining mantle temperatures from the volcanic products of the High Lava Plains.

The geodynamic aspects of this project will be directed by PI Kincaid who will work with a graduate student on numerical modeling and with the student and Ross Griffiths of ANU on the laboratory modeling (see URI budget justification and Griffith's letter of support).

Field aspects of the project will be highly coordinated, both between the various geochemical/petrologic targets and the seismic imaging. Because of these shared field responsibilities, fund requests for field support are included in all PI's budgets. Geological strip maps to accompany seismic sections with attended targeted dating and geochemical characterization will be coordinated by Grunder, but executed by Grunder, Hart, Carlson, Grove, Duncan and students. The strip maps will serve as a training ground for undergraduates. At least four undergraduate students per year will be engaged in various parts of the geophysical and geological fieldwork and will help in aspects of data collection and analysis and will participate in mini-research projects to be presented at meetings. PIs Grunder and Hart have a record of engaging undergraduates in research projects and seeing the work to student presentation at regional or national meetings. The sampling of the crust via xenoliths/xenocrysts and isotopic analysis of silicic crustal melts will be a part of the Ph.D. thesis project of Denise Giles, supervised by Grunder. Another Ph.D. student will focus on geochronology and the relationship of volcanic rocks to the development of structures of the High Lava Plains and northern Basin and Range. Geochemical and petrologic studies of the Hawkes Valley eruptive center will be directed by Hart and will be part of a Ph.D. project for a graduate student at Miami. These studies will involve Carlson in aspects of the radiogenic isotope work, both Duncan and Carlson in geochronological measurements, and Keller in both gravity and detailed site location of the refraction lines through these areas. The work on Newberry will build on the detailed field mapping and basic geochemistry to be done by USGS collaborator Julie Donnelly-Nolan. Experimental work on these basalts will be directed by Grove and will constitute a component of a Ph.D. thesis study at MIT. Carlson will be responsible for completing the trace element data obtained by Donnelly-Nolan, for B, Sr, Nd, Hf and Pb isotopic analysis of whole rocks where not already available, and for volatile (H, C, S, F, Cl) determinations in melt inclusions by ion-probe. Grove, Hart and Carlson will similarly interact on the study of primitive basalts from the Jordan Valley volcanic field with the experimental petrology being conducted at MIT under the direction of Grove, additional chemical and isotopic analyses done by Hart and students at Miami, boron and volatile analyses by Carlson at DTM and Ar-Ar age determinations as needed directed by Duncan with the assistance of his Research Associate John Huard.

Geochemical studies will take advantage of the diverse facilities available at DTM, OSU and Miami University. Work at Miami University, under the direction of Hart, will include major and some trace element analyses by DCP and radiogenic isotope (Sr, Nd and Pb) analyses by the students involved in the study of the Hawkes Valley center and Jordan Valley volcanic field using the Miami University Triton thermal ionization mass spectrometer. Trace element analyses by ICP-MS (OSU and DTM), laser-ablation ICP-MS analyses of Pb in K-feldspars (OSU), and oxygen isotope analyses (OSU) will be performed under the direction of Grunder and Carlson. Duncan will direct Ar-Ar age dating. We have budgeted for 100 Ar-Ar age determinations over the course of this project. About half of these age dates will be focused on and around the geophysical transects, about 20 will be used toward the work of Hart and Carlson on the pre 10 Ma volcanic rocks for better documentation of the transition from flood to sparse HAOT volcanism, about 20 for regional studies targeting interactions between post 10 Ma volcanism and 10 will be used toward correlation of ignimbrites. We feel that this division of responsibility and sharing of facilities will result in the most efficient and cost effective approach to the wide-ranging geochemical/petrologic analyses proposed here.

Table 4 below lists the yearly budgets per PI or institution as a means to clearly convey the proposed budget distribution between the PIís that we feel is needed to accomplish the tasks described above.

Table 4: Budget division per PI

PI	Institution	Year 1	Year 2	Year 3	Year 4	Total
Carlson	DTM/CIW	$28,362	$29,800	$28,266	$26,301	$112,729
James	DTM/CIW	$129,321	$225,258	$184,212	$118,081	$656,872
Fouch	ASU	$137,084	$204,751	$166,150	$132,196	$640,181
Grove	MIT	$87,906	$103,967	$107,147	$110,455	$409,475
Grunder	OSU	$74,539	$102,852	$121,708	$79,864	$378,963
Duncan	OSU	$31,242	$34,070	$18,491	$18,059	$101,862
Hart	Miami U	$66,510	$62,013	$36,024	$33,143	$197,690
Keller/Harder	UTEP	$82,152	$549,685	$78,644	$55,352	$765,833
Kincaid	URI	$35,994	$75,008	$98,521	$49,928	$259,451
Total		**$673,110**	**$1,387,404**	**$839,163**	**$623,379**	**$3,523,056**

5) Broader Impacts: Integrative and Outreach Activities

The very nature of a multidisciplinary project of this magnitude provides fertile ground for student training across many disciplines in the solid earth sciences. As described in section 4, this project will produce a number of Ph.D. theses as well as offer field experience to the large number of undergraduates involved in this project, particularly in the active seismic experiment. These students, though concentrating on their individual research areas, will be exposed to all research results, and the variety of research approaches used by the collaborators of this proposal. These students will use the data they gather as the basis for senior, M.S., or Ph.D. theses. Our experience shows that students greatly benefit from a project such as this in several ways. First, they receive hands-on experience in data collection and the use of modern technology, which makes the lecture material they have received come alive. Second, they participate in a project of discovery in contrast to canned lab exercises. We have found this experience to create increased interest and motivation that often lasts throughout their student careers. Third, the data processing and analysis is computer intensive so the students will hone their computer skills. Fourth, we have observed that a major field experience and interactions with faculty and fellow students are a key life-experience that greatly broadens their horizons. The end result will be that several students will receive invaluable real-world experience and technical training.

To ensure multidisciplinary connections, we will hold a yearly workshop for all participants in this project. The workshop will include short field trips so that all participants can be exposed to the same salient aspects of the study area. These workshops will be open to anyone interested in the scientific goals of this project with the goal of bringing in the knowledge and expertise of the many scientists who have worked on this general subject.

Several of the PIís are actively involved in efforts to compile, preserve, and facilitate the use of geoscience data and have been involved in the *Geoinformatics* initiative since its inception. PIs Carlson, Fouch, and Keller have successfully obtained NSF/ITR grants to develop databases and cyberinfrastructure. The compositional and age data collected for volcanic rocks from this project will be tied to the magmatic evolution of the western US through integration into the NAVDAT [*Walker et al.*, 2001] geochemical database for Cenozoic igneous rocks from western North America (navdat.geo.ku.edu; PI Carlson). The availability of this database will allow us to compare trends in volume, location, and/or composition of High Lava Plains magmatism with the broader Cenozoic volcanic record of western North America to look for large, plate-scale, controls over the volcanic record. The animation of volcanic activity that can be found on the NAVDAT website is an early example of the utility of such a data compilation.

The compilation of multiple data sets featured in the SWGeoNet project (www.geoinformaticsnetwork.org/swgeonet; PIs Keller and Fouch) would be repeated for this project so that we can undertake a fully integrated study that takes advantage of all available data. The goal of the recently funded large Information Technology Research project GEON (GEOscience Network; www.geongrid.org; PI Keller) is to provide the critical initial cyberinfrastructure necessary to facilitate *Geoinformatics*. Thus, we are in an excellent position to access existing database construction efforts and to structure our own data compilation, integration, and archival efforts so that they will require minimum effort and be consistent with existing cyberinfrastructure efforts. The proposed project is an excellent example of the complexity of the scientific questions being addressed by the earth science community whose answers require integrative and innovative approaches employing large, complex data sets. From the beginning, the data sets developed during this project will be constructed to facilitate integrated data sharing and analysis between project group members. From the perspective of outreach, education, dissemination of scientific data and results, and preservation of the results of the publicís investment in basic research, it is appropriate that a significant aspect of the proposed project will be a concerted database and dissemination effort that is aimed beyond our own group. One component of this effort will include the use of the experimental study to develop models for predicting temperature-pressure conditions and H_2O content of mantle melting. These models will be made available in published form and as user-friendly computer programs so that they can be used by the broader community. Another exciting coupled research and outreach component is through the GeoWall (www.geowall.org), a low-cost 3-D visualization tool. One of the primary developers of GeoWall applications is Marvin Simkin at ASU, who will be involved in the project to provide the integral component of animations and visualizations of the dataset acquired here.

In this project we also have the opportunity to interact with a number of federal agencies responsible for various aspects of this area beyond the obvious connections with the USGS. These opportunities include contacts with a variety of land management agencies and groups (BLM, National Forest Service, local Cattlemen's Associations). Besides their input on issues such as permitting and providing secure locations for seismic deployments, our past interactions with the local representatives of these agencies have shown us their sincere interest in the geology around them. We expect to provide public presentations to these groups concerning this project and its goals and will issue invitations to local representatives of these agencies, for example Larry Chitwood and Bob Jensen of the Deschutes National Forest (Newberry area), Terry Geisler from the BLM Burns District (Harney Basin), Jonathan Westfall from the BLM Vale District (SE Oregon) and Robert Skinner (Jordan Valley), past-President of the Oregon Cattlemen's Association to accompany us on the workshop field excursions. The work in the Newberry area will have high visibility owing to the recent interest in potential central Oregon volcanic hazards owing to the uplifting area west of the Sisters region and the continuing efforts of the USGS collaborator Dr. Julie Donnelly-Nolan to define the volcanic hazard in this area.

References

Achauer, U., J.R. Evans, and D.A. Stauber, High-resolution seismic tomography of compressional wave velocity structure at Newberry Volcano, Oregon Cascade Range, *J. Geophys. Res. 93*, 10135-10147, 1988.

Armstrong, R.L., W.H. Taubeneck, and P.O. Hales, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and the Sr isotopic composition, Oregon, Washington and Idaho, *Geol. Soc. Am. Bull. 81*, 3513-3536, 1977.

Arndt, N.T., and U. Christensen, The role of lithospheric mantle in continental flood volcanism: Thermal and geochemical constraints, *J. Geophys. Res. 97*, 10967-10981, 1992.

Averill, M.G., G.R. Keller, K.C. Miller, P. Sroda, T. Bond, and A. Velasco, Data fusion in Geophysics: Seismic tomography and crustal structure in Poland as an example, *Int. J. Applied Earth Observation and Geoinformation*, *in review*, 2004.

Bacon, C.R., P.E. Bruggman, R.L. Christiansen, M.A. Clynne, J.M. Donnelly-Nolan, and W. Hildreth, Primitive magmas at five Cascades volcanic fields: melts from hot, heterogeneous sub-arc mantle, *Canadian Mineralogist 35*, 397-423, 1997.

Baker, M.B., T.L. Grove, and R. Price, Primitive basalts and andesites from the Mt. Shasta region, N. California: products of varying melt fraction and water content, *Contrib. Mineral. Petrol. 118*, 111-129, 1994.

Bartels, K.S., R.J. Kinzler, and T.L. Grove, High pressure phase relations of primitive high-alumina basalts from Medicine Lake volcano, northern California, *Contrib. Mineral. Petrol. 108*, 253-270, 1991.

Bondre, N.R. and W.K. Hart, Flow chemistry and vent alignments from the Jordan Valley volcanic field, Oregon: insights into the evolution of monogenetic volcano fields: *Geological Society of America Abstracts with Programs*, 36, 75, 2004.

Bostock, M.G. and J. C. VanDecar, Upper mantle structure of the northern Cascadia subduction zone, *Can. J. Earth Sci.* 32, 1-12, 1995.

Brandon, A.D., and G.G. Goles, A Miocene subcontinental plume in the Pacific Northwest: geochemical evidence, *Earth Planet. Sci. Lett.* 88, 273-283, 1988.

Brueseke, M.E., and W.K. Hart, Complex magma system development in northern Nevada and the role of episodic basalt injection into the crust, *Geol. Soc. Amer. Abst. Prog. 33*, A302, 2001.

Brueseke, M.E., and W.K. Hart, Mid-Miocene flood basalt volcanism in southeastern Oregon: new insights on an old problem, *Geol. Soc. Amer. Abst. Prog. 34*, 364, 2002.

Brueseke, M.E., and W.K. Hart, Compositional diversity in mid-Miocene mafic lavas from the southeastern Oregon Plateau, *Geol. Soc. Amer. Abst. Prog. 35*, 549, 2003.

Brueseke, M.E., K.A. Shoemaker, and W.K. Hart, New tectonic implications derived from southern Oregon Plateau basaltic volcanism: defining the Owyhee Block, *Geol. Soc. Amer. Abst. Prog. 34*, A-38, 2002.

Brueseke, M.E., W.K. Hart, and M.T. Heizler, Distribution and Geochronology of Oregon Plateau (U.S.A.) Flood Basalt Volcanism: the Steens Basalt Revisited, *J. Volcan. Geotherm. Res.*, *submitted*, 2003a.

Brueseke, M.E., W.K. Hart, A.R. Wallace, M.T. Heizler, and R.J. Fleck, Mid-Miocene volcanic field development in northern Nevada: new age constraints on the timing of Santa Rosa-Calico volcanism, *Geol. Soc. Amer. Abst. Prog. 35*, 63, 2003b.

Brueseke, M.E., W.K. Hart and K.A. Shoemaker, Re-evaluating the "Owyhee-Humboldt" eruptive center: relationships between voluminous Middle Miocene silicic volcanism and the Owyhee Plateau: *Geological Society of America Abstracts with Programs*, **36**, 97, 2004.

Camp, V.E. and M.E. Ross, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest, J. Geophys. Res. 109, doi:10.129/2003JB002838, 2004.

Carlson, R.W., Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle, *Geochim. Cosmochim. Acta 48*, 2357-2372, 1984.

Carlson, R.W., and W.K. Hart, Crustal genesis on the Oregon Plateau, *J. Geophys. Res. 92*, 6191-6206, 1987.

Carlson, R.W., G.W. Lugmair, and J.D. Macdougall, Reply to a critical comment by D. J. DePaolo on "Columbia River volcanism: the question of mantle heterogeneity or crustal contamination", *Geochim. Cosmochim. Acta* 47, 845-846, 1983.

Carlson, R.W., D.G. Pearson, F.R. Boyd, S.B. Shirey, G. Irvine, A.H. Menzies and J.J. Gurney, Re-Os systematics of lithospheric peridotites: implications for lithosphere formation and preservation, R.W. Carlson, D.G. Pearson, F.R. Boyd, S.B. Shirey, G. Irvine, A.H. Menzies and J.J. Gurney, *in* Proc. 7th Int. Kimberlite Conf., Volume 1: Cape Town, Red Roof Design, edited by Gurney, J.J., Gurney, J.L., Pascoe, M.D., and Richardson, S.H., p. 99-108, 1999.

Carlson, R.W., F.R. Boyd, S.B. Shirey, P.E. Janney, T.L. Grove, S.A. Bowring, M.D. Schmitz, J.C. Dann, D.R. Bell, J.J. Gurney, S.H. Richardson, M. Tredoux, A.H. Menzies, D.G. Pearson, R.J. Hart, A.H. Wilson, and D. Moser, Continental growth, preservation, and modification in southern Africa, *GSA Today 10*, 1-7, 2000.

Catchings, R.D., and W.D. Mooney, Crustal structure of east central Oregon: Relation between Newberry volcano and regional crustal structure, *J. Geophys. Res. 93*, 10081-10094, 1988.

Chesley, J.T. and J. Ruiz, Crust-mantle interaction in large igneous provinces: implications from the Re-Os isotope systematics of the Columbia River flood basalts, *Earth Planet. Sci. Lett.* 154, 1-11, 1998.

Christiansen, R.L., G.R. Foulger, and J.R. Evans, Upper-mantle origin of the Yellowstone hotspot, *Geol. Soc. Amer. Bull. 114*, 1245-1256, 2002.

Christiansen, R.L., and E.H. McKee, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, in *Geol. Soc. Amer. Mem.*, edited by R.B. Smith, and G.P. Eaton, pp. 283-311, 1978.

Coney, P.J., D.L. Jones, and J.W.H. Monger, Cordilleran suspect terranes, *Nature 288*, 329-333, 1980.

Conrad, W.K., The mineralogy and petrology of compositionally zoned ash flow tuffs, and related silicic volcanic rocks, from the McDermitt caldera complex, Nevada-Oregon, *J. Geophys. Res.*, *89* 8639-8664, 1984.

Conrey, R.M., D.R. Sherrod, P.R. Hooper, and D.A. Swanson, Diverse, primitive magmas in the Cascade arc, northeast Oregon and southern Washington, *Canadian Mineralogist 35*, 367-396, 1997.

Conrey, R.M., J.M. Donnelly-Nolan, and E.M. Taylor, The north-central Cascade margin: exploring petrologic and tectonic intimacy in a propagating intra-arc rift, *MARGINS 2000 Meeting Field Guide* 61, 2000.

Cross, T.A., and R.H. Pilger, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States, *Am.J.Sci. 278*, 865-902, 1978.

DePaolo, D.J., Comment on "Columbia River volcanism: the question of mantle heterogeneity or crustal contamination", *Geochim. Cosmochim. Acta* 47, 841-844, 1983.

Dickinson, W.R., Mesozoic forearc basin in central Oregon, *Geology 7*, 166-170, 1979.

Dodson, A., B.M. Kennedy and D.J. DePaolo, Helium and neon isotopes in the Imnaha Basalt, Columbia River Basalt Group: evidence for a Yellowstone plume source, *Earth Planet. Sci. Lett.* 150, 443-451, 1997.

Draper, D.S., Late Cenozoic bimodal magmatism in the northern Basin and Range province of southeastern Oregon, *J. Volcan. Geotherm. Res. 47*, 275-295, 1991.

Ekren, E.B., D.H. McIntyre, E.H. Bennett, and R.F. Marvin, Cenozoic stratigraphy of western Owyhee County, Idaho, in *Cenozoic Geology of Idaho*, edited by B. Bonnichsen, and R.M. Breckenridge, pp. 215-235, Idaho Bureau of Mines Geology Bulletin, 1982.

Elkins-Tanton, L.T., T.L. Grove, and J. Donnelly-Nolan, Hot, shallow mantle melting under the Cascades volcanic arc, *Geology 29*, 631-634, 2001.

Evans, J.C., A. Griscom, P.F. Halvorson, and M.L. Cummings, Tracking the western margin of the North American Craton beneath southeastern Oregon: a multidisciplinary approach, in *Tectonic and Magmatic Evolution of the Snake River Volcanic Province*, edited by B. Bonnichsen, C.M. White, and M. McCurry, Idaho Geological Survey Bull. 30, p. 35-57, 2002.

Fitton, J.G., D. James, P.D. Kempton, D.S. Ormerod and W.P. Leeman, The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the western United States, *J. Petrol. Special Lithosphere Issue,* 331-349, 1988.

Fouch, M.J., Mantle deformation beneath the southern Cascadia subduction zone, *Eo*s *Trans. AGU*, 85*(47),* Fall Meet. Suppl., Abstract T24B-05, 2004.

Fouch, M.J., K.M. Fischer, E.M. Parmentier, M.E. Wysession, and T.J. Clarke, Shear wave splitting, continental keels, and patterns of mantle flow, *J. Geophys. Res*., 105, 6255-6276, 2000.

Gaetani G.A., M.S. Ghiorso, R.O. Sack, M. Hirschmann, P.D. Asimow, MELTS, *Science* 282, 1834-1835, 1998.

Gaetani, G.A., and T.L. Grove, The influence of water on melting of mantle peridotite, *Contrib. Mineral. Petrol. 131*, 323-346, 1998.

Gallagher, K., and C.J. Hawkesworth, Dehydration melting and the generation of continental flood basalts, *Nature 358*, 57-59, 1992.

Geist, D., and M. Richards, Origin of the Columbia Plateau and Snake River Plain: deflection of the Yellowstone plume, *Geology 21*, 789-792, 1993.

Ghioso, M.S., and R.O. Sack, Chemical mass transfer in magmatic processes: IV, A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures, *Contrib. Min. Petrol.* 119, 197-212, 1995.

Gilbert, L.Y., M.E. Brueske, D.C. Snyder, and W.K. Hart, A record of mid-Miocene explosive volcanism and rift basin development in the Santa Rosa-Calico volcanic field, Nevada, *Geol. Soc. Amer. Abst. Prog. 35*, 7, 2003.

Gorman, A.R., R.M. Clowes, R.M. Ellis, T.J. Henstock et al., Deep Probe: imaging the roots of western North America, *Can. J. Earth Sci. 39*, 375-398, 2002.

Grad, M., G.R. Keller, H. Thybo, and A. Guterch, Lower lithospheric structure beneath the Trans European Suture Zone from POLONAISE í97 seismic profiles, *Tectonophys. 360*, 153-168, 2002.

Greene, R.C., Petrology of the welded tuff of Devine Canyon, southeastern Oregon, *U.S. Geol. Surv. Prof. Paper* P0797, 26 pp, 1973.

Gripp, A.E., and R.G. Gordon, Young tracks of hotspots and current plate velocities, *Geophys. J. Int.*, *150*, 321-361, 2002.

Grove, T.L., R.J. Kinzler, and W.B. Bryan, Fractionation of mid-ocean ridge basalt (MORB). In *Mantle Flow and Melt Migration at Mid-Ocean Ridges*, Phipps-Morgan, J., et al., eds., American Geophysical Monograph 71, 281-311, 1993.

Grove, T.L., S.W. Parman, S.A. Bowring, R.C. Price, and M.B. Baker, The role of an H_2O-rich fluid component in the generation of primitive basaltic andesites and andesites from the Mt. Shasta region, N California, *Contrib. Mineral. Petrol. 142*, 375-396, 2002.

Grove, T.L., S.W. Parman, and J.C. Dann, Conditions of magma generation for Archean komatiites from the Barberton Mountainland, South Africa, in *Mantle Petrology: Field Observations and High Pressure Experimentation: A tribute to Francis R. (Joe) Boyd*, edited by Y. Fei, C.M. Bertka, and B.O. Mysen, pp. 155-167, The Geochemical Society, Special Publication 6, Houston, 1999.

Grunder, A.L., Material and thermal roles of basalt in crustal magmatism: case study from eastern Nevada, *Geology* 23, 952-956, 1995.

Hall, P. and C. Kincaid, Melting, dehydration and the dynamics of off-axis plume-ridge interaction, *Geochem. Geophys. Geosyst.*, 4(9), 8510, 2003.

Hall, P., and C. Kincaid, Melting, dehydration and the geochemistry of off-axis plume-ridge interaction, *Geochem. Geophys. Geosyst.*, in press, 2004.

Hall, C.E., K.M. Fischer, E.M. Parmentier, and D.K. Blackman, The influence of plate motions on three-dimensional back arc mantle flow and shear wave splitting, *J. Geophys. Res.*, *105*, 28,009-28,033, 2000.

Hart, W.K., Chemical and isotopic evidence for mixing between depleted and enriched mantle, northwestern U.S.A., *Geochim. Cosmochim. Acta 49*, 131-144, 1985.

Hart, W.K. and M.E. Brueseke, Eruptive diversity and styles of silicic volcanism in the mid-Miocene Santa Rosa-Calico volcanic field, northern Nevada: *Geological Society of America Abstracts with Programs*, **36**, 11, 2004.

Hart, W.K., J.L. Aronson, and S.A. Mertzman, Areal distribution and age of low-K, high-alumina olivine tholeiite magmatism in the northwestern Great Basin, *Geol. Soc. Amer. Bull.*, *95*, 186-195, 1984.

Hart, W.K., R.W. Carlson, and S.B. Shirey, Radiogenic Os in primitive basalts from the northwestern U.S.A.: implications for petrogenesis, *Earth Planet. Sci. Lett. 150*, 103-116, 1997.

Hauri, E., J.Wang, J.E. Dixon, P.L. King, C. Mandeville and S. Newman, SIMS analysis of volatiles in silicate glasses 1. Calibration, matrix effects and comparisons with FTIR, *Chem. Geol.* 183, 99-114, 2002.

Hay, D.E., R.F. Wendlandt, and G.R. Keller, The origin of Kenya rift Plateau-type flood phonolites: Integrated petrologic and geophysical constraints on the evolution of the crust and upper mantle beneath the Kenya rift, *J. Geophys. Res. 100*, 10549-10557, 1995.

Higgins, M.W., Petrology of Newberry volcano, central Oregon, *Geol. Soc. Amer. Bull. 84*, 455-488, 1973.

Hildreth, W., Gradients in silicic magma chambers: implications for lithospheric magmatism, *J. Geophys. Res.* 86, 10153-10192, 1981.

Hole, J.A., Nonlinear high-resolution three-dimensional seismic travel time tomography, *J. Geophys. Res. 97*, 6553-6562, 1992.

Hooper, P.R., The Columbia River flood basalt province: current status, in *Large Igneous Provinces*, edited by J.J. Mahoney, and M.F. Coffin, pp. 1-28, American Geophysical Union, Washington, 1997.

Hooper, P.R., G.B. Binger, and K.R. Lees, Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon, *Geol. Soc. Amer. Bull. 114*, 43-50, 2002.

Hooper, P.R., and C.J. Hawkesworth, Isotopic and geochemical constraints on the origin and evolution of the Columbia River basalt, *J. Petrol. 34*, 1203-1246, 1993.

Humphreys, E.D., K.D. Dueker, D.L. Schutt, and R.B. Smith, Beneath Yellowstone: evaluating plume and nonplume models using teleseismic images of the upper mantle, *GSAToday 10*, 1-7, 2000.

Huppert, H.E. and R.S.J. Sparks, The generation of granitic magmas by intrusion of basalt into continental crust, *J. Petrol.* 29, 599-624, 1988.

James, D.E., M.J. Fouch, J.C. VanDecar, and S. van der Lee, Tectospheric structure beneath southern Africa, *Geophys. Res. Lett. 28*, 2485-2488, 2001.

James, D.E., F.R. Boyd, D. Schutt, D.R. Bell, and R.W. Carlson, Xenolith constraints on seismic velocities in the upper mantle beneath southern Africa, *Geochem., Geophys., Geosyst.* Doi:10.1029/2003GC000551*,* 2004.

Johnson, J.A., and A.L. Grunder, The making of intermediate composition magma in a bimodal suite: Duck Butte Eruptive Center, Oregon, USA, *J. Volcan. Geotherm. Res. 95*, 175-195, 2000.

Johnson, J.A., R.L. Nielsen, and M.R. Fisk, Plagioclase-hosted melt inclusions in the Steens Basalt, southeastern Oregon, *Petrologiya 4*, 266-272, 1996.

Jordan, B.T., Age-progressive volcanism of the Oregon High Lava Plains: Overview and evaluation of tectonic models, in *Plumes, Plates, and Paradigms*, edited by G.R. Foulger et al., Spec. Paper Geol. Soc. Amer., in press, 2004.

Jordon, B.T., D.W. Graham and A.L. Grunder, Do helium isotopes in basalts of the Oregon High Lava Plains implicate a Yellowstone plume component? *Geol. Soc. Amer. Abstr. Programs* 32, 150, 2000.

Jordan, B.T., A.L. Grunder, R.A. Duncan, and A.L. Deino, Geochronology of Oregon High Lava Plains volcanism: Mirror image of the Yellowstone hotspot?, *J. Geophys. Res.*, *in press,* 2004.

Keller, G.R., T.G. Hildenbrand, R. Kucks, D. Roman, and A.M. Hittleman, Upgraded gravity anomaly base of the United States, *The Leading Edge 21*, 366-367, 2002.

Keller, G.R., J. Mechie, L.W. Braille, W.D. Mooney, and C. Prodehl, Seismic structure of the uppermost mantle beneath the Kenya rift, *Tectonophys. 236*, 201-216, 1994.

Kincaid, C., and R. W. Griffiths, Thermal evolution of the mantle during rollback subduction, *Nature*, 425, 58-62, 2003a.

Kincaid, C. and R. W. Griffiths. Spatial and temporal variability in the circulation and thermal evolution of the mantle in subduction zones: Insights from 3-D laboratory experiments, *EOS Trans. Amer. Geophys. Union* , Fall Meeting, 2003b.

Kincaid, C. and R. W. Griffiths, Variability in mantle flow and temperatures within subduction zones. *Geochem. Geophys. Geosyst.*, 5, Q06002, doi:10.1029/2003GC000666, 2004.

Kincaid, C. and P. Hall, The role of back-arc spreading in circulation and melting at subduction zones, *J. Geophy. Res* , 208, 2240-2254, 2003.

King, S.D., and D.L. Anderson, An alternative mechanism of flood basalt formation, *Earth Planet. Sci. Lett. 136*, 269-279, 1995.

King, S.D., and D.L. Anderson, Edge-driven convection, *Earth Planet. Sci. Lett. 160*, 289-296, 1998.

Kinzler, R., Melting of mantle peridotite at pressures approaching the spinel to garnet transition: application to mid-ocean ridge basalt petrogenesis, *J. Geophys. Res. 102*, 853-874, 1997.

Kinzler, R.J., and T.L. Grove, Primary magmas of mid-ocean ridge basalts 2. applications, *J. Geophys. Res. 97*, 6907-6926, 1992.

Knight, J.E., Brueseke, M.E., and Hart, W.K., Physical, petrographic and geochemical characterization of ash flow volcanism: the mid-Miocene Cold Springs Tuff of the Santa Rosa-Calico volcanic field, Nevada: *Geological Society of America Abstracts with Programs*, **36**, 77-78, 2004.

Lassak, T.M., M.J. Fouch, C.E. Hall, and E. Kaminski, Seismic characterization of mantle flow in subduction systems: Can we resolve a hydrated mantle wedge? *Eos Trans. AGU*, 85*(47),* Fall Meet. Suppl., Abstract T23D-06, 2004.

Lawrence, R.D., Strike-slip faulting terminates the Basin and Range province in Oregon, *Geol. Soc. Amer. Bull. 87*, 846-850, 1976.

Le Roux, P.J., S.B. Shirey, L. Benton, E.H. Hauri and T.D. Mock, In-situ, multiple-multiplier, laser ablation ICP-MS measurement of boron isotopic composition at the nanogram level, *Chem. Geol.* 203, 123-138, 2004.

Leeman, W.P., Olivine tholeiitic basalts of the Snake River Plain, Idaho, in *Cenozoic Geology of Idaho*, edited by B. Bonnichsen, and R.M. Breckenridge, pp. 181-191, Idaho Bureau of Mines and Geology Bulletin, 1982.

Leeman, W.P., Boron and other fluid-mobile elements in volcanic arc lavas; implications for subduction processes, in *Subduction Top to Bottom*, edited by G.E. Bebout, D.W. Scholl, S.H. Kirby, and J.P. Platt, pp. 269-276, Geophysical Monograph, 1996.

Leeman, W.P., J.S. Oldow, and W.K. Hart, Lithosphere-scale thrusting in the western U.S. Cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks, *Geology 20*, 63-66, 1992.

Linneman, S.R., and J.D. Myers, Magmatic inclusions in Holocene rhyolites of Newberry Volcano, central Oregon, *J. Geophys. Res. 95*, 17666-17691, 1990.

Lipman, P.W., H.J. Prostka, and R.L. Christiansen, Cenozoic volcanism and plate tectonic evolution of the western United States, I, *Phil.Trans.R.Soc. London, Ser. A 271*, 217-248, 1972.

Louie, J.N., W. Thelen, S. B. Smith, J. B. Scott, M. Clark, S. Pullammanappallil, The northern Walker Lane refraction experiment: Pn arrivals and the northern Sierra Nevada root, *Tectonophysics* 388, p.253-269, 2004.

Maclean, J.W., Geology and geochemistry of Juniper Ridge, Horsehead Mountain and Burns Butte: implications for the petrogenesis of silicic magmas on the High Lava Plains, southeastern Oregon, unpublished PhD thesis, Oregon State University, 1994.

MacLeod, N.S., D.R. Sherrod, L.A. Chitwood, and R.A. Jensen, Geologic map of Newberry volcano, Deschutes, Klamath, and Lake counties, Oregon, *USGS Miscellaneous Investigations Map I2455, scale 1:62,500 and 1:24,000*, 1995b.

MacLeod, N.S., G.W. Walker, and E.H. McKee, Geothermal significance of eastward increase in age of upper Cenozoic rhyolitic domes in southeastern Oregon, in *Proceedings of the Second*

United Nations Symposium on the Development and Use of Geothermal Resources, pp. 465-474, 1975.

Maloy, A.K., M.E. Brueske, C.B. Minturn, and W.K. Hart, The generation of intermediate composition magmas in a bimodal setting: evidence from the Santa Rosa-Calico volcanic field, Nevada, *Geol. Soc. Amer. Abst. Prog. 35*, 5, 2003.

Manduca, C.A., L.T. Silver, and H.P. Taylor, ^{87}Sr/^{86}Sr and ^{18}O/^{16}O isotopic systematics and geochemistry of granitoid plutons across a steeply-dipping boundary between contrasting lithospheric blocks in western Idaho, *Contrib. Mineral. Petrol. 109*, 355-372, 1992.

McCaffrey, R., M.D. Long, C. Goldfinger, P.C. Zwick, J.L. Nabelek, C.K. Johnson and C. Smith, Rotation and plate locking at the southern Cascadia subduction zone, *Geophys. Res. Lett.* 27, 3117-3120, 2000.

McCurry, M., D.W. Rodgers, S.S. Hughes, K.B. Price, K.C. Scarberry, and M.T. Ford, Mantle-derived mass transfer to continental crust along the Yellowstone hotspot track, *Geol. Soc. Amer. Abstr. Prog.* 34, 85, 2002.

McKee, E.H., W.A. Duffield, and R.J. Stern, Late Miocene and early Pliocene basaltic rocks and their implications for crustal structure, northeastern California and south-central Oregon, *Geol. Soc. Amer. Bull. 94*, 292-304, 1983.

Mechie, J., G.R. Keller, C. Prodehl, M.A. Khan, and S.J. Gaciri, A model for the structure, composition, and evolution of the Kenya rift, *Tectonophys. 278*, 95-119, 1997.

Meltzer, A., R. Rudnick, P. Zeitler, A. Levander, G. Humphreys, K. Karlstrom, G. Ekstrom, R. Carlson, T. Dixon, M. Gurnis, P. Shearer, and R. van der Hilst, USArray Initiative, *GSAToday 9*, 8-10, 1999.

Montelli, R., G. Nolet, F.A. Dahlen, G. Masters, E.R. Engdahl, S.-H. Hung, Finite-frequency tomography reveals a variety of plumes in the mantle, *Science* 303, 338-343, 2004.

Nabelek, J.L., X.-Q. Li, S. Azevado, J. Braunmiller, A. Fabritius, B. Leitner, A. Trehu, and G. Zandt, A high-resolution image of the Cascadia subduction zone from teleseismic converted phases recorded by a broadband seismic array, *EOS, Trans. Amer. Geophys. Union 74*, 431, 1993.

Norman, M.D. and W.P Leeman, Geochemical evolution of Cenozoic-Cretaceous magmatism and its relation to tectonic setting, southwestern Idaho, USA, *Earth Planet. Sci. Lett.* 94, 78-96, 1989.

Oldow, J.S., Evolution of a late Mesozoic back-arc fold and thrust belt, northwestern Great Basin, U.S.A, in *Geodynamics of back-arc regions*, edited by R.L. Carlson, and K. Kobayashi, pp. 245-274, Tectonophys., 1984.

Parman S.W., T.L Grove, Harzburgite melting with and without H_2O: Experimental data and predictive modeling, *J. Geophys. Res.* 109, Art. No. B0221, 2004.

Peng, X., and E.D. Humphreys, Crustal velocity structure of the eastern Snake River Plain and the Yellowstone swell, *J. Geophys. Res. 103*, 7171-7186, 1998.

Pierce, K.L., and L.A. Morgan, The track of the Yellowstone hot spot: Volcanism, faulting, and uplift, in *Regional Geology of Eastern Idaho and Western Wyoming*, edited by P.K. Link, M.A. Kuntz, and L.B. Platt, pp. 1-53, Geological Society of America Memoir, 1992.

Pierce, K.L., L.A. Morgan, and R.W. Saltus, Yellowstone plume head: postulated tectonic relations to the Vancouver slab, continental boundaries, and climate, *U.S. Geological Survey Open File Report 2000-498*, 25, 2000.

Reidel, S.P., T.L. Tolan, P.R. Hooper, M.H. Beeson, K.R. Fecht, R.B. Bentley, and R.L. Anderson, The Grande Ronde Basalt, Columbia River basalt group: stratigraphic descriptions and correlations in Washington, Oregon and Idaho, in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province* Spec. Pap. 239, edited by S.P. Reidel and P.R. Hooper, pp. 21-54, Geol. Soc. Amer., Boulder, 1989.

Richards, M.A., R.A. Duncan and V.E. Courtillot, Flood basalts and hot-spot tracks: plume heads and tails, *Science* 246, 103-107, 1989.

Rondenay, S., M.G. Bostock, and J. Schragge, Multiparameter two-dimensional inversion of scattered teleseismic body waves. 3. Application to the Cascadia 1993 data set, *J. Geophys. Res. 106*, 30795-30807, 2001.

Rytuba, J.J., and E.H. McKee, Peralkaline ash flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada, *J. Geophys. Res. 89*, 8616-8628, 1984.

Saltzer, R., and E.D. Humphreys, Upper mantle P-wave structure of the eastern Snake River Plain and its relationship to geodynamic models of the region, *J. Geophys. Res. 102*, 11,829-11,841, 1997.

Schmitz, M.D., S.A. Bowring, M.J. de Wit and V. Gartz, Neoarchean stabilization of the western Kaapvaal Craton: implications for Witwatersrand basin subsidence and the formation of continental lithosphere, *Lithos*, in press, 2004.

Schutt, D.L., E.D. Humphreys, and K.G. Dueker, Vp/Vs structure beneath the Snake River Plain; imaging upper mantle partial melt, *EOS, Trans. Amer. Geophys. Union 78*, 492-493, 1997.

Schutt, D.L., E.D. Humphreys, and K. Dueker, Anisotropy of the Yellowstone hot spot wake, eastern Snake River Plain, Idaho, *Pure and Applied Geophysics 151*, 443-462, 1998.

Sherrod, D.R., and J.G. Smith, Quaternary extrusion rates of the Cascade Range, northwestern Unites States and southern British Columbia, *J. Geophys. Res. 95*, 19465-19747, 1990.

Shirey, S.B., J.W. Harris, S.H. Richardson, M.J. Fouch, D.E. James, P. Cartigny, P. Deines, and F. Viljoen, Diamond genesis, seismic structure, and evolution of the Kaapvaal-Zimbabwe craton, *Science* 297, 1683-1686, 2002.

Shoemaker, K.A., and W.K. Hart, Temporal controls on basalt genesis and evolution on the Owyhee Plateau, Idaho and Oregon, in *Tectonic and Magmatic Evolution of the Snake River Plain Province*, edited by B. Bonnichsen, C.M. White, and M. McCurry, Idaho Geological Survey Bulletin 30, 313-328, 2003.

Silver, P.G. and W.E. Holt, The mantle flow field beneath western North America, *Science* 295, 1054-1057, 2002.

Simiyu, S.M., and G.R. Keller, An integrated analysis of lithospheric structure across the East African Plateau based on gravity anomalies and recent seismic studies, *Tectonophys. 278*, 291-313, 1997.

Simiyu, S.M., and G.R. Keller, An integrated geophysical analysis of the upper crust of the southern Kenya rift, *Geophys. J. Int. 147*, 543-561, 2001.

Smith, R.L., and R.G. Luedke, Potentially active volcanic lineaments and loci in western conterminous United States, in *Explosive Volcanism*, pp. 47-66, National Academy Press, Washington, 1984.

Song, T.A., D.V. Helmberger, and S.P. Grand, Low velocity zone atop the 410 km seismic discontinuity in the northwestern US, *EOS, Trans. Amer. Geophys. Union* 84, F1401, 2003.

Streck, M.J., Partial melting to produce high-silica rhyolites of a young bimodal suite: compositional constraints among rhyolites, basalts, and metamorphic xenoliths from the Harney Basin, Oregon, *Int. J. Earth Sci. 91*, 583-593, 2001.

Streck, M.J., and A.L. Grunder, Facies and facies variations of the Rattlesnake Tuff, eastern Oregon, *Bull. Volcan. 57*, 151-169, 1995.

Streck, M.J., and A.L. Grunder, Compositional gradients and gaps in the high-silica rhyolites of the Rattlesnake Tuff, southeastern Oregon, *J. Petrol. 38*, 133-163, 1997.

Streck, M.J., and A.L. Grunder, Enrichment of basalt and mixing of dacite in the rootzone of a large rhyolite chamber: inclusions and pumices from the Rattlesnake Tuff, Oregon, *Contrib. Mineral. Petrol. 136*, 193-212, 1999.

Streck, M.J., J.A. Johnson, and A.L. Grunder, Field Guide to the geology of the Rattlesnake Tuff and High Lava Plains, eastern Oregon, *Oregon Geology 61*, 64-76, 1999.

Suppe, J., C. Powell, and R. Berry, Regional topography, seismicity, Quaternary volcanism, and the present day tectonics of the western United States, *Amer. J. Sci. 275A*, 397-417, 1975.

Trehu, A.M., T.M. Asudeh, T.M. Brocher, J.H. Luetgert, W.D. Mooney, J.L. Nabelek, and Y. Nakamura, Crustal architecture of the Cascadia forearc, *Science 266*, 237-243, 1994.

Vallier, T.L., Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Implications for the geologic evolution of a complex island arc, in *Geology of the Blue Mountains region of Oregon, Idaho and Washington: Petrology and tectonic evolution of pre-Tertiary rocks of the Blue Mountains Region*, edited by T.L. Vallier, and H.C. Brooks, pp. 125-209, USGS Professional Paper, 1995.

van der Lee, S., and G. Nolet, The upper-mantle S-velocity structure of North America, *J. Geophys. Res.*, *102*, 22815-22838, 1997.

Walker, G.W., Cenozoic ash-flow tuffs of Oregon, *The Ore Bin 32*, 97-115, 1970.

Walker, G.W., Some implications of late-Cenozoic volcanism to geothermal potential in the High Lava Plains of south-central Oregon, *The Ore Bin* 36, 109-119, 1974.

Webb, S.J., R.G. Cawthorn, T. Nguuri, and D.E. James, Gravity modeling of Bushveld Complex connectivity supported by Southern African Seismic Experiment results, *S. Afr. J. Geol*, *107* (1/2), 207-218, 2004.

Webb, S.J., D.E. James, and T. Nguuri, The integration of gravity data with seismological results from the Kaapvaal Craton Seismic Experiment: an assessment of isostatic balance., in *6th Biennial Conference of the South African Geological Association*, pp. 1-6, South African Council on Geosciences, Cape Town, RSA, 1999.

Wells, R.E., and P.L. Heller, The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation in the Pacific Northwest, *Geol. Soc. Amer. Bull. 100*, 325-338, 1988.

Williams, H., Newberry volcano and central Oregon, *Geol. Soc. Amer. Bull. 46*, 253-304, 1935.

Wilson, A.H., S.B. Shirey and R.W. Carlson, Archaean ultra-depleted komatiites formed by hydrous melting of cratonic mantle, *Nature* 423, 858-861, 2003

Yogodzinski, G.M., J.M. Lees, T.G. Churikova, F. Dorendorf, G. Woeerner, and O.N. Volynets, Geochemical evidence for the melting of subducting oceanic lithosphere at plate edges, *Nature 409*, 500-504, 2001.

Zelt, C.A., and R.B. Smith, Seismic traveltime inversion for 2-D crustal velocity structure, *Geophys. J. Int. 108*, 16-34, 1992.

Zoback, M.L., E.H. McKee, R.J. Blakely, and G.A. Thompson, The northern Nevada rift: regional tectono-magmatic relations and middle Miocene stress direction, *Geol. Soc. Amer. Bull. 106*, 371-382, 1994.