KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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Faculty: *CHRISTINE SIDDOWAY, MEGAN ANDERSON*, Colorado College, *ERIC ERSLEV*, University of Wyoming
Students: *MOLLY CHAMBERLIN*, Texas A&M University, *ELIZABETH DALLEY*, Oberlin College, JOHN *SPENCE HORNBUCKLE III*, Washington and Lee University, *BRYAN MCATEE*, Lafayette College, *DAVID OAKLEY*, Williams College, *DREW C. THAYER*, Colorado College, *CHAD TREXLER*, Whitman College, *TRIANA N. UFRET*, University of Puerto Rico, *BRENNAN YOUNG*, Utah State University.

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PETROLOGIC CONSTRAINTS ON SHEAR WAVE ANISOTROPY IN THE BIGHORN MOUNTAINS: INSIGHTS FROM GARNET PERIDOTITE MANTLE XENOLITHS AND REGIONAL PETROFABRICS

TRIANA N. UFRET, University of Puerto Rico
Research Advisor: Aaron Cavosie

INTRODUCTION

Mantle xenoliths offer a window to the composition, age, and structure present in the deep subsurface of the Earth, thus providing a link between surface exposures and geophysical observations (Barnhart, 2009). In this study three mantle xenoliths from the Homestead (Montana) and Kelsey Lake (Colorado) kimberlites were analyzed in order to characterize their physical and chemical properties to help interpret regional seismic anisotropy patterns discovered in the Bighorn Mountains (Wyoming). Petrofabrics, hydrous minerals, and observations of textures such as rims or interstitial recrystallization of certain minerals offer clues about chemical processes that affected the mantle rocks. These observations are needed to assess the effects of mineralogy and petrofabrics upon seismic wave behavior. More specifically, the purpose of this study is to investigate the xenolith samples for the presence of either shape preferred orientations (SPOs) or lattice preferred orientations (LPOs). Petrographic analysis is the first step to address whether or not regional fabrics exist in the mantle beneath the Bighorn Mountains which may be the cause of observed seismic anisotropy.

GEOLOGICAL CONTEXT

The largest fields of kimberlites in the US are found in the Archean Wyoming Craton (~2.7 Ga) (Coopersmith et al., 2003). The kimberlites contain xenoliths at some localities, including the Homestead kimberlite (central Montana) and the Kelsey Lake kimberlite (Colorado), sites that provided the samples for this study (Figure 1). Petrologic and fabric analysis of such samples is the principle way to acquire direct information about mineral-scale anisotropy in the mantle underlying the Wyoming Craton that may influence seismic shear wave velocities (Karato et al., 2008). Kimberlites and mantle xenoliths have not been found in the Bighorn Mountains, therefore representative mantle xenoliths from peripheral locations were used.

The Homestead (HS) kimberlites were emplaced around 50 Ma ago (Carlson, 2004) in the Grassrange area, containing rocks composed of shale and siltstone (Hearn, 2004). Compositions for xenoliths range from harzburgites (containing garnet, spinel or both), and garnet lhezorlites to chromite dunites in lesser amounts (Irving et al., 2003; Hearn, 2004). Depths of up to 150 km have been established for the origin for Homestead peridotite xenoliths. Garnets in the xenoliths sometimes display complex textures of spinel inclusions and orthopyroxene (opx) grains within the vicinity of garnet crystals, an indication of changes in pressure and temperatures for incomplete re-equilibration near the garnet-spinel stability boundary (Hearn, 2004).

The Kelsey Lake (KL) kimberlites are part of the State Line District Kimberlites along the border of Wyoming and Colorado, emplaced at 390 Ma (Coopersmith et al., 2003). The kimberlites contain diamonds, xenoliths of lherzolite, harzburgite, eclogite, members of the Cr-poor megacryst suite and xenocrysts. They are predominantly volcaniclastic, with lesser hypabyssal and epiclastic portions, and they are extensively altered. The host rock for KL kimberlite intrusions is the 1.4 Ga Sherman granite batholith (Coopersmith et al., 2003). In the xenoliths, olivine and opx are replaced by serpentine and calcite, although purple garnets, green Cr-diopside and black spinel are present (Coopersmith et al., 2003). Previous geochemical and petrologic studies determined that the kimberlites result from lithospheric melting

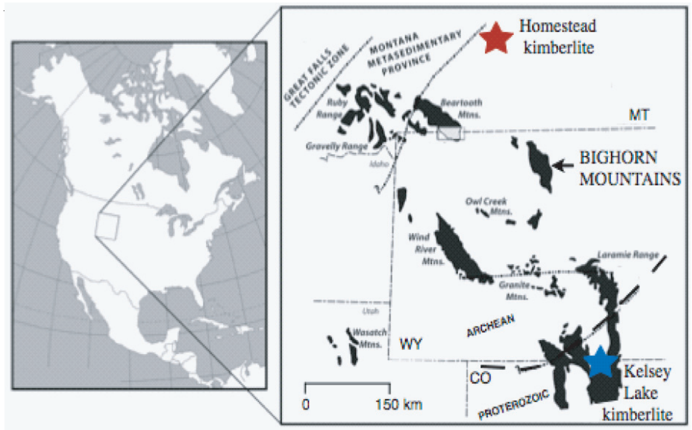

Figure 1. Geographic location of Homestead kimberlite in Montana (red star), Kelsey Lake kimberlite at the Colorado-Wyoming state line (blue star), and Bighorn Mountains in Wyoming. (After Mueller et al., 2010)

metasomatic events at shallower depths (Coopersmith et al., 2003).

Previous studies of mantle peridotite xenoliths from Russian kimberlites using electron back scatter diffraction (EBSD) have documented significant LPOs in olivine. The LPOs have been attributed to observed seismic anisotropy (Bascou et al., 2011).

Causes of anisotropy in Earth materials

Anisotropy is a material or wave property which is directionally dependent; seismic anisotropy is the cause of different wave speeds for different propagation directions of waves through earth materials. Both LPOs and SPOs in minerals can cause seismic anisotropy (Karato et al., 2008). Many types of anisotropy characterize each area of Earth's interior. Fractures and open cracks in the brittle environment of the upper crust are commonly associated with anisotropy that lines up with tectonic stresses (Anderson, 2005). Shear zones, dikes and alignment of seismic fast axes of anisotropic minerals by shearing are all causes of anisotropy of the lower crust (Anderson, 2005) including SPOs; plastic deformation is also a cause of anisotropy (Karato et al., 2008). LPOs in olivine or other anisotropic mantle minerals are assigned to upper mantle anisotropy (Bascou et al., 2011). Being the predominant mineral in the mantle, olivine is the leading mineral involved in experimental research for seismic anisotropy (Karato et al., 2008). The effect of wave propagation and shear wave splitting from olivine LPOs can be affected principally by stress, temperature and water content (Karato et al., 2008). Studies of Karato et al. (2008) reveal the [100] axes of olivine and the (010) planes are deformed nearly parallel to flow direction for dry samples, after being exposed to large strain (>1.5%). Karato et al. (2008) also tested olivine dislocation with the presence of water and concluded that the dominant slip systems in the mineral changes in its presence. With a significant amount of water (200-1,200 ppm) high stresses, and low temperatures, olivine crystal fast directions align 90° to flow directions (Long and Silver, 2009). Shear wave splitting is acutely responsive to the influence of anisotropy (Crampin, 1985). Because shear wave splits are recorded in three components, the direction of LPO and SPO can be inferred from seismic data (Crampin, 1985).

METHODS

Shear wave splitting

Shear wave splitting (SWS) analyses was accomplished by the SWS team, a collaborative work of three students: Drew Thayer, John Hornbuckle and the first author (Ufret). My evaluation of seismic data from a subset of ~20 stations was accomplished through Splitlab, designed to enable a visual and quantitative processing of seismic data (Wüstefeld et al., 2008). The data was used by Hornbuckle and Thayer to plot pierce points maps and backazimuth direction plots in order to characterize the anisotropy. For details about analytical processes see Hornbuckle (2011, this volume).

Xenolith petrography

Using polarized light microscopy, a petrographic analysis of mantle xenolith thin sections was performed. Two billets of each rock sample were cut and sent for the production of thin sections at the University of Wisconsin. Criteria for the selection of cutting directions include apparent mineral lineations or fabrics visible in hand sample, where present. One thin section was cut parallel to the inferred mineral lineations and the other perpendicular to the first in order to maximize the likelihood of intersecting fabrics. Identification of minerals, textures, deformation or any other features such as oriented grains was documented. A gypsum accessory plate was used to qualitatively detect the presence of LPOs based on the ability to determine the optical continuity of the minerals of interest.

HAND SAMPLE DESCRIPTION

Three mantle xenoliths were analyzed. Brief descriptions of each hand sample, along with their place of origin, are given below.

KL01: Kelsey Lake kimberlite, Colorado-Wyoming State Line
Garnet bearing peridotite. Part of a spherical xenolith, 22 cm long, 11 cm wide and 6 cm high; green. The sample has a 1.5 cm wide altered "crust". Garnet phenocrysts as well as bright clinopyroxenes (cpx), Cr- diopside, are readily identifiable on the surface.

HS01: Homestead kimberlite, central Montana.
Garnet bearing peridotite. A dense ultramafic rock with nodular shape, 12 cm long, 9 cm wide and 10 cm high. Composed of dark green groundmass with garnet phenocrysts which have a dark purple coloration and range from 4 to 10 mm.

HS02 : Homestead kimberlite, central Montana.
Garnet bearing peridotite. A dark green subangular ultramafic rock, 7.5 cm long, 6.4 cm wide and 5 cm high. Olivine phenocrysts are visible as well as very small vitreous grains of yellow to green pyroxenes.

RESULTS

Kelsey Lake
KL01

Primary minerals are garnet, olivine (rarely preserved), cpx, opx, and spinel (Figure 2). Secondary minerals include serpentine, phlogopite, muscovite, calcite and opaque oxides (Figure 3). Holocrystalline grains with porphyritic texture are present, composed of euhedral garnets and subhedral olivine. Garnet grains are not zoned, but rimmed by a spinel bearing

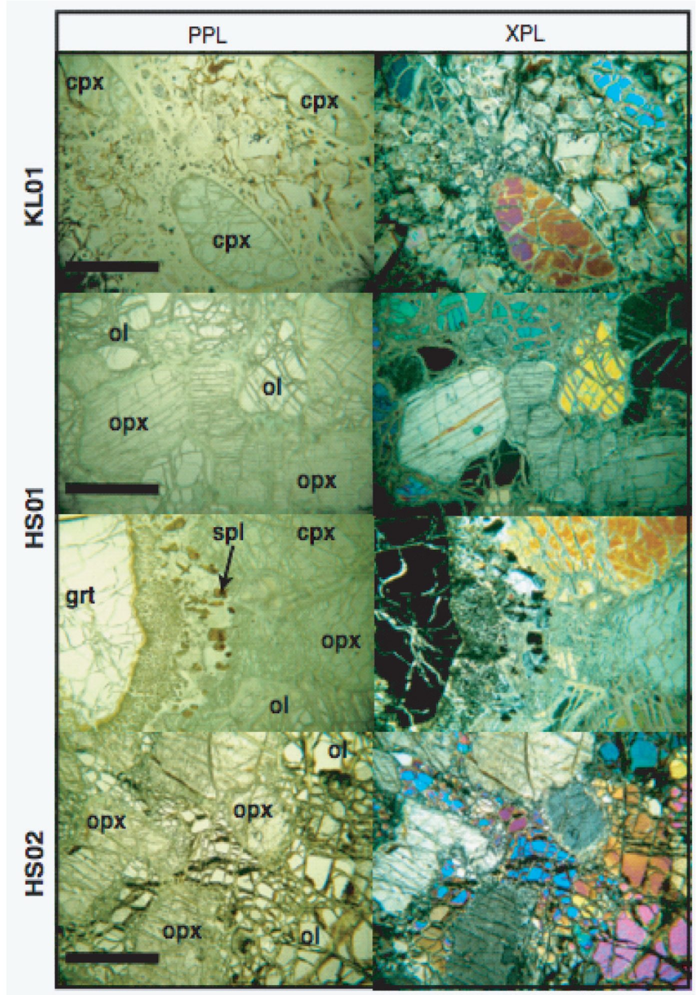

Figure 2. Primary minerals in studied xenoliths. Scale bars are 1 mm. Abbreviations: Ol = olivine, Grt = garnet, Opx = orthopyroxene, Cpx = clinopyroxene, PPL = plane polarized light, XPL = cross polarized light.

Homestead
HS01

Primary minerals are garnet, olivine, cpx, opx, and spinel (Figure 2). Secondary minerals include actinolite (rims on opx), phlogopite and opaque oxides (Figure 3). The sample contains holocrystalline grains with interlocking subhedral crystals, medium in grain size. Intergrowths of garnet with olivine are few. Double coronas surround garnet grains. The inner corona may contain kelyphite, a spinel bearing symplectite (Godard et al., 2000), in contact with garnet. The inner corona contains symplectite texture and outer corona contains euhedral spinel (Figure 2).

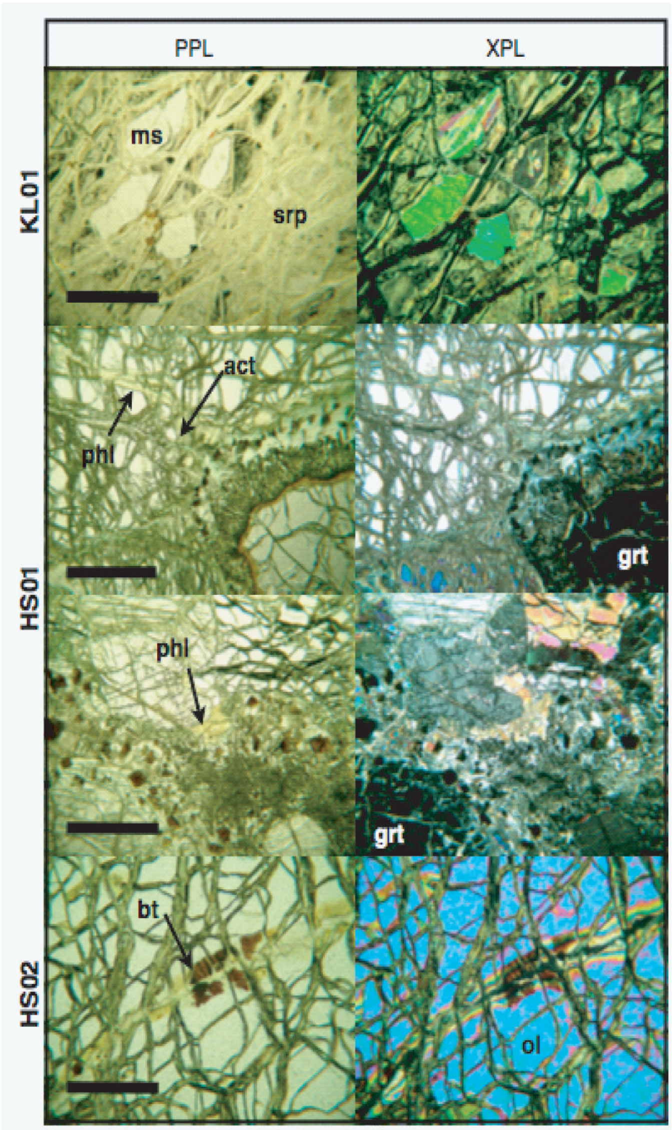

Figure 3. Secondary and hydrous minerals in studied xenoliths. Scale bars are 1 mm. Abbreviations: Ol = olivine, Spl = spinel, Srp = serpentine Phl = phlogopite, Ms = muscovite, Act = actinolite, PPL = plane polarized light, XPL = cross polarized light.

HS02

Primary minerals are garnet, poikilitic spinel, olivine, cpx and opx (Figure 2). Secondary minerals include phlogopite, biotite, actinolite (rims on opx) and opaque oxides (Figure 3). The sample contains holocrystalline grains with interlocking subhedral crystals, cumulophyric and inequigranular grains. Intergrowths of orthopyroxene with olivine are few. Double coronas surround garnet grains (Figure 2). The inner corona may contain kelyphite, a spinel bearing symplectite (Godard et al., 2000), in contact with garnet. The inner corona contains symplectite texture and outer corona contains euhedral spinel. Olivine fracture fillings in HS02-01 contain a black isotropic mineral (possibly graphite), that was not identified in the other two samples.

Shape preferred orientations (SPO's) and lattice preferred orientations (LPO's)

HS01-02 contains elongated and oriented grains of cpx and opx. Garnet grains are also aligned in the same direction (Figure 4). The presence of oriented minerals in a preferred shape denotes SPOs in the HS01 mantle xenolith.

For LPOs a gypsum plate was used to observe the consistency of birefringence color intensities for different grains of the same mineral because the gypsum plate allows to verify if they are in optical continuity. No sets of primary peridotite minerals were observed in optical continuity as determined through gypsum plate observation is samples KL01, HS01 or HS02.

Summary of petrography

Mineral percentages for each sample are contained in Table 1. All samples are garnet bearing peridotites. All HS garnets have two distinctive coronas. For HS garnets, the inner corona is very fine grained and less than 250 µm in width. The outer corona has small grains containing euhedral spinel crystals, and no more than 150 µm in length. For KL garnets, the corona is no more than 250 µm. SPOs are only present in sample HS01. Elongated grains of cpx and opx are parallel and aligned, as well as garnet grains. Tentative LPOs were found in the HS01 analyzed mantle xenoliths.

DISCUSSION

The Kelsey Lake samples are pervasively altered. Serpentine, muscovite and phlogopite are minerals that record alteration of primary minerals to hydrous phases during a chemical change that involved fluid transport. These findings are consistent with an explanation proposed by Coopersmith et al. (2003) of deep melting up to 200 km and metasomatism events

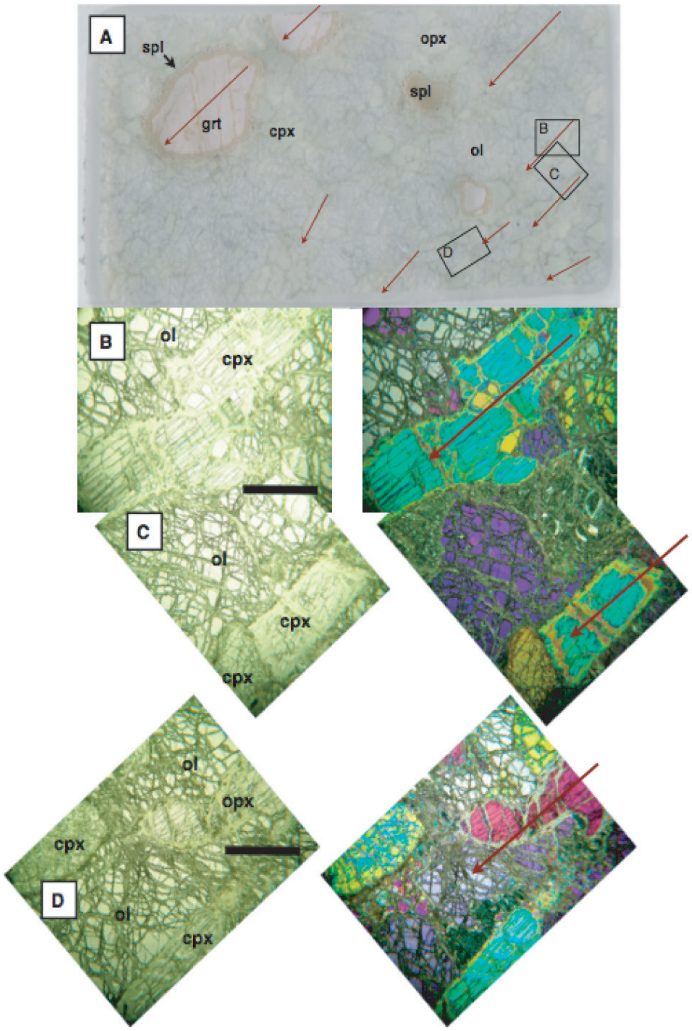

Figure 4. Oriented opx, cpx and grt grains found in sample HS01-02. Plane polarized light (left) and cross polars with gypsum plate images (right). Scale bars are 1 mm in length. Abbreviations: Ol = olivine, Grt = garnet, Opx = orthopyroxene, Cpx = clinopyroxene, Spl = spinel, PPL = plane polarized light, XPL = cross polarized light. A) Photograph of HS01-02 thin section, red arrows represent aligned or elongate grains, black boxes constrain the area represented by: B) Photograph of elongate cpx grain with gypsum plate inserted C) Photograph of cpx grain parallel to cpx in B, with gypsum plate inserted, D) Photograph of a group of elongate and aligned opx and cpx grains with gypsum plate inserted.

of fluids by diffusion or pervasive infiltration, is an important process for enrichment of the upper mantle (Winter, 2001), leading to textural recrystallization and growth of new minerals in veins or matrix. However, the depth and timing of alteration is difficult to constrain.

The alteration may have occurred before, during, or after the eruption of the kimberlite. Because muscovite is present in the samples from KL Ar/Ar dating may be able to constrain a relative age for the event responsible for the alteration. If the alteration of the rock occurred before the kimberlite eruption, the alteration took place in mantle depths. However, even if the alteration event predated eruption, the resulting age would be likely reflect post-kimberlite eruption cooling, rather than an ancient mantle metasomatic event. If the alteration occurred during the kimberlite eruption the resulting age would be similar to the emplacement of the kimberlite. Alteration after kimberlite eruption may have taken place at earth's surface; as a consequence the resulting age would be younger than the emplacement of the kimberlite.

Hydrous phases in the KL samples constitute more than 50% of the mineralogy (Table 1). With a range in water content of 200-1,200 ppm present in olivine dominated samples together with high stresses and low temperatures the dominant slip system of olivine change by 90° away from flow directions (Karato et al., 2008). Hydrous mineral abundance for HS samples are 1% or less for HS01 and <3% for HS02.

Because all the mantle xenoliths are garnet bearing (Table 1), a depth for the origin of these rocks can be broadly constrained to be below 100 km where garnet is the stable Al phase. Spinel, being the shallower phase (above 100 km), is present as euhedral grains inside garnet coronas, indicating a re-equilibration of the Al phase with decreasing depth. These textures record the transportation of the xenolith from its depth of origin to the surface or near surface within the kimberlite. Therefore, the results can be compared with modeled seismic anisotropy at depths below ~ 100km.

SPO's were identified in sample HS01-02, where cpx and opx grains are occasionally elongated and aligned parallel to each other. All garnet grains in this sample follow the same direction of alignment (Figure 4). Because a mantle xenolith's course of transportation is erratic, the orientation of the sample is unobtainable. The remaining samples did not contain groups of aligned minerals, or other detectible petrographic fabrics.

Table 1. Mineral percentage approximations in sampled peridotite xenoliths from Homestead kimberlite (HS) and Kelsey Lake kimberlite (KL).

Sample	Ol	Grt	Opx	Cpx	Spl	Srp	Phl	Ms	Act	Fe oxide*	Opq	tp
KL01-01	<<1	12	-	1	5	>50	-	1	-	27	1	<1
KL01-02	<<1	7	<1	1	2	>60	-	2	-	20	1	<1
HS01-01	59	6	16	14	4	-	<1	-	1	-	<1	-
HS01-02	50	10	18	16	5	-	<1	-	1	-	<1	-
HS02-01	45	1	25	3	5	-	1	-	<1	-	20	<1
HS02-02	48	1	29	8	3	-	3	-	<1	-	8	<1

Abbreviation : Ol = olivine, Grt = garnet, Opx = orthopyroxene, Cpx = clinopyroxene, Spl = spinel, Srp = serpentine, Phl = phlogopite, Ms = muscovite, Act = actinolite, Opq = opaque minerals, tp = trace phases.
*Fine grained, primarily associated with alteration of Opx.

The spatial relationship between the Bighorn Mountains and the kimberlites used for this study is an important issue. Because there are no kimberlites directly over the Bighorn Mountain region, this study analyzed kimberlites within the region. The HS kimberlite is ~200 km north and the KL kimberlite ~ 300 km southeast of the Bighorn Mountains (Figure 1). Both the Bighorn Mountains and the HS kimberlites are part of the Archean Wyoming Craton. However, the KL kimberlite is part of the Proterozoic Yavapai province. The fact that the KL kimberlite does not belong to the Wyoming craton and is separated by a suture zone (terrain boundary) limits the application of petrofabric information derived from these samples to the interpretation of seismic wave behavior in the Wyoming Province. The HS mantle xenoliths, however, may be appropriate samples that can be used in future petrofabric studies for modeling seismic anisotropy beneath the Bighorn Mountains.

CONCLUSIONS

The Kelsey Lake mantle xenoliths contain garnet, olivine, clinopyroxene, spinel and orthopyroxene as primary minerals. Secondary minerals include serpentine, phlogopite, muscovite, calcite, and opaque oxides. The Kelsey Lake mantle xenoliths are pervasively altered and contain more than 50% of hydrous minerals. Processes for these results could be major element depletion and later enrichment of the Wyoming craton which was proposed by Hearn (2004). The spatial distribution and other factors for the KL kimberlites can be problematic for directly relating their specimens to the Bighorn mountains.

The Homestead mantle xenoliths contain garnet, spinel, olivine, clinopyroxene and orthopyroxene as primary minerals. Secondary minerals include phlogopite, biotite, actinolite and opaque oxides. SPOs can be denoted by alignments and elongation of cpx and opx grains in HS01-02. No patterns or overall orientations were observed in the samples KL01 or HS02. No certain LPOs were found, however HS01 birefringence orders for olivine grains were noticeably alike, nevertheless none where identical. All mantle xenoliths are garnet bearing, and all garnets are rimmed. Compositionally derived symplectite texture is present in HS garnet's inner coronas. Al re-equilibration phase is denoted by the presence of spinel bearing coronas in garnet. The depth of origin of the specimens analyzed is constrained by a minimum of 100 km. Therefore, the seismic models that result from the SWS that include these depths can be interpreted with guidance from the results obtained in this study.

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