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Key Points:

- Revised geothermometer and new geobarometer calculations place the xenoliths at mid-lithospheric depths of 45–55 km
- The temperatures at these depths are 200°C–300°C warmer than expected for normal lithosphere beneath 90-Myr-old seafloor
- The adjacent lithosphere is inferred to have been reheated rapidly during the voluminous Ko'olau shield volcano magmatism

Supporting Information:

- Supporting information S1
- Supporting information S2
- Supporting information S3
- Supporting information S4

Correspondence to:

I. Guest,
imani_guest@brown.edu

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Extensive Magmatic Heating of the Lithosphere Beneath the Hawaiian Islands Inferred From Salt Lake Crater Mantle Xenoliths

Imani Guest¹ , Garrett Ito², Michael O. Garcia², and Eric Hellebrand³

¹Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, ²Department of Earth Sciences, University of Hawai'i at Mānoa, Honolulu, HI, USA, ³Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands

Abstract An ongoing challenge in studies of the oceanic upper mantle is how intraplate hotspots impact the thermal structure of the lithosphere. To address this issue at the Hawaiian hotspot, we analyze mineral compositions for a petrographically diverse suite of garnet pyroxenite xenoliths from the Salt Lake Crater (SLC) rejuvenation stage, volcanic tuff ring in Honolulu. Garnet-clinopyroxene geobarometry and two-pyroxene geothermometry indicate equilibrium pressures of 13–18 kbar and temperatures of 1000°C–1100°C. These pressures place the xenoliths at mid-lithospheric depths of 45–55 km, with temperatures 200°C–300°C hotter than expected for normal 90-Myr-old oceanic lithosphere. Garnet and clinopyroxene occur as discrete primary grains, as well as exsolution blebs and lamellae, with lateral dimensions up to several hundred microns. Compositions within garnet and pyroxene grains are remarkably uniform and display no systematic variation with distance to grain boundaries. Together, these observations indicate that the calculated pressures and temperatures reflect the thermal state of the lithosphere under which the xenoliths last equilibrated. We attribute the elevated lithospheric temperatures under Honolulu primarily to the heating by magma as it penetrated the lithosphere during rejuvenation magmatism and the voluminous shield magmatic stage. We anticipate such magmatic heating to be common among all Hawaiian volcanoes, supporting conclusions of a recent study of earthquakes beneath Hawai'i Island. This local lithospheric thermal anomaly may also contribute to the enigmatically weak flexural response of the lithosphere due to volcano loading along the Hawaiian hotspot chain.

Plain Language Summary The Hawaiian-Emperor volcano chain in the Pacific Ocean is one of the most well-known surface expressions of a mantle hotspot, having persisted over the past 82 Myrs. This continued influx of magma and heat has impacted the thermal structure of the Pacific tectonic plate to an unknown degree. This study directly addresses this issue using rocks (xenoliths) that originated in the lithospheric plate, but became engulfed in magma as it passed through the plate and eventually erupted at Salt Lake Crater, a late-stage volcanic ring tuff on the island of O'ahu. We use the chemical compositions of the minerals, as well as their modes of occurrence found in the mantle xenoliths to calculate the temperatures and pressures (i.e., depths) at which the xenoliths equilibrated. We find that the xenoliths equilibrated at depths where temperature was significantly higher than expected for normal oceanic lithosphere having the same age as the Hawaiian lithosphere. We infer that these anomalous temperatures were introduced by magma that rose from the hot mantle through the lithospheric plate during the volcanic construction of the island of O'ahu. Such magmatic heating may impact how the plate flexes and faults due to the enormous weight of this and the other Hawaiian volcanoes.

1. Introduction

Volcanic activity along the Hawaiian-Emperor chain has persisted for at least 82 Myrs and is considered to be one of the most prominent surface expressions of a hot spot caused by a mantle plume (Wolfe et al., 2009). Hawaiian volcanism is subdivided into four sequential stages: preshield, shield, postshield, and rejuvenation (Clague & Dalrymple, 1987). Rejuvenated volcanism is a perplexing phenomenon during which magmatism occurs after a 0.5–2 Myr hiatus in volcanism at a substantial distance (>100 km) away from the center of the hotspot where the main shield phase is active. Mantle xenoliths are commonly erupted during

Figure 1. (a) Map of the island of Oahu and (b) the main Hawaiian Islands. The location of Salt Lake Crater is indicated by the red star.

the rejuvenation stage when magma ascends rapidly from the mantle (Clague, 1987). Salt Lake Crater (SLC) in Honolulu on the Hawaiian island of Oahu (Figure 1) is part of the Honolulu Volcanics and was formed during the rejuvenation phase at about 0.25 Ma, which is ~ 2 Myrs after the end of shield volcanism associated with the Ko'olau volcano ($\sim 34,000 \text{ km}^3$ total) upon which SLC rests (Ozawa et al., 2005; Robinson & Eakins, 2006).

SLC is renowned for abundant garnet-bearing mantle xenoliths, making it a classic site for investigating the interaction between the Hawaiian hotspot and the Pacific lithospheric mantle (e.g., Sen et al., 2005). Xenoliths from SLC have been studied extensively for the past half century (e.g., Beeson & Jackson, 1970; Bizimis et al., 2013, 2005; Keshav et al., 2007). Several previous studies have suggested the SLC xenoliths originated at depths of the lower lithosphere or asthenosphere (e.g., 16–22 kbar; Keshav et al., 2007), however a recent study suggested the SLC garnet pyroxenite xenoliths last equilibrated at mid-lithospheric depths (10–32 kbar) prior to being picked up by ascending SLC magma (Bizimis et al., 2013) based on temperatures calculated with the two pyroxene geothermometer and the BK geobarometer from Brey and Köhler (1990).

If the xenoliths originated in the lithosphere, information about their preextraction temperatures and pressures may provide insight into the thermal structure of the lithosphere. Knowledge of the lithospheric geotherm beneath hotspots such as Hawai'i is important for addressing questions about the origin of hotspot swells (Detrick & Crough, 1978), the dynamics of plume-plate interaction (Bellas et al., 2020; Moore et al., 1998), the rheology of the lithosphere as reflected by its flexural response to the weight of the volcanic edifices (Bellas et al., 2020; Pleus et al., 2020; Zhong & Watts, 2013), as well as the interaction between the lithosphere and magma penetrating it (Mittelstaedt et al., 2008).

In this study, we present petrography and mineral compositions for a diverse suite of garnet-bearing pyroxenite xenoliths from SLC, and utilize a new geobarometer designed for garnet pyroxenites (Beyer et al., 2015) as well as an updated geothermometer (Putirka, 2008; per. comm. 2015) to improve our understanding of the thermal structure of the lithosphere beneath the Hawaiian chain. The results suggest large excess temperatures (200°C – 300°C) at mid-lithospheric depths (45–55 km), which requires a mechanism of rapid and substantial heating of the lithosphere during hotspot activity.

2. Sample Petrography and Textures

Three main types of ultramafic xenoliths are found at SLC: spinel peridotites, garnet pyroxenites, and dunites (e.g., Sen et al., 2005). Dunites are typically shallow cumulates (depths of 3–15 km) crystallized from plume-derived magma, whereas the spinel peridotite and pyroxenite xenoliths are from greater depths in

Figure 2. Representative backscattered electron (BSE) images of samples (a) C01, (b) SL2, (c) X01, (d) X02, (e) X17, and (f) X20.

the upper mantle (Bizimis et al., 2005; Keshav et al., 2007; Sen et al., 2005). Composite xenoliths with two of these three rock types are also found at SLC. The garnet-bearing pyroxenites are typically black to dark gray with reddish garnets in hand specimen and easily distinguished from the light green spinel lherzolites. The textures of the SLC mantle xenoliths range widely: porphyroclastic, foliated, and equigranular with common exsolution lamellae in pyroxenes (Sen et al., 2005). Six garnet pyroxenite samples were selected from a suite of >100 SLC xenoliths at the University of Hawai'i at Mānoa (Table S1; Figure 2). These six were chosen based on three main criteria: (1) nearly uniform, weakly deformed textures to minimize complications from multiple thermal histories; (2) minimal interstitial melt derived from the host magma (samples X01, X20, and C01 have patchy, thin [<0.01 mm wide] glass along some grain boundaries with thin [<0.05 mm wide] reaction zones consisting of fine grained clinopyroxene (cpx) and phlogopite); and (3) the presence of garnet, cpx, and orthopyroxene (opx) for calculating temperatures and pressures for the xenoliths prior to being picked up by the host melt (Table S1). One of our samples, C01, is a composite xenolith with dunite in sharp contact with garnet pyroxenite (Table S1). Elongate phlogopite grains within the dunite occur along and are oriented perpendicular to the lithology contact. The samples we examined range from igneous textures (poikilitic, samples X01, and C01) to equigranular.

The mineralogy of the six SLC garnet pyroxenites is dominated (>50 vol.%) by cpx. The cpx is usually large (0.5–1.5 mm), subhedral (Figure 2), and bounded by olivine, spinel, or garnet, with variable amounts of exsolved opx (Figures 2c and 2e). The larger cpx grains in the SLC pyroxenites have been interpreted to be a primary phase (e.g., Keshav et al., 2007). Cpx also occurs as thin, exsolved lamellae, 20–200 μm across, in large (>1 mm) opx crystals. Xenoliths X01 and SL2 exhibit coarser pyroxene (200–400 μm wide) and garnet (gt) exsolution (400–800 μm wide). The wider lamellae in these samples may be a result of slower or more cooling compared to the other samples, although we found no clear correlation between samples with or without the wider lamellae and the temperatures derived from the geothermometry. The dimensions of the exsolved minerals will be used as evidence for in situ residence times of the xenoliths, which is crucial to our interpretations of the thermal structure of the lithosphere.

Opx grains occur as large (0.5–1.5 mm), subhedral crystals, with thin (10–20 μm wide) cpx exsolution lamellae. However, in xenolith X20, opx grains are small (50–100 μm wide) and rare. More typically, opx is present as exsolved lamellae (20–100 μm wide) in large cpx grains.

Garnet occurs in many forms in the SLC xenoliths: primary, large 0.5–1 mm crystals (samples X20 and C01), exsolution lamellae or blebs in pyroxene (samples X01 and X17) and as rims/coronas on spinel (samples

X02 and SL2; Figures 2d and 2b). Spinel within garnet commonly show embayed and amoeboidal grain boundaries. Large garnets were considered by Keshav et al. (2007) as primary crystals.

Olivine is present in all of the studied samples unlike the SLC suites analyzed by others (e.g., Keshav et al., 2007). Its modal abundance varies greatly in our samples but is always subordinate to cpx. Olivine ranges in size and mode of occurrence from discrete, larger crystals (0.2–1.0 mm) to small inclusions in large cpx. Triple junctions between adjacent olivine grains are rare and only found within the dunite portion of the composite xenolith C01. Olivine is typically fractured with fluid inclusions along some fractures. The grain margins of olivine do not show evidence of alteration.

All but one of the studied xenoliths (X20) contain spinel. It typically occurs as discrete, small (0.1–0.2 mm wide) crystals or as an exsolved phase in large cpx and opx crystals. When exsolved in cpx, spinel has blade-like forms (20–150 μm long), and occurs as rhomboids (30–150 μm), lamellae (20–100 μm), or rods varying 30–120 μm wide. Spinel color ranges from brown and green (Mg-rich) to black (opaque, Fe-rich).

All of the samples also contain trace amounts (<1 vol.%) of phlogopite, a common hydrous mineral in SLC garnet pyroxenites (Keshav et al., 2007). Phlogopite occur as small (10–100 μm) crystals along grain boundaries and is undeformed. Phlogopite is considered to be of secondary origin in SLC garnet pyroxenites (Keshav et al., 2007).

3. Analytical Methods

Mineral compositions of pyroxene and garnet were determined using the SOEST JXA-8500F JEOL Hyperprobe at the University of Hawai'i at Mānoa. High precision major and minor element analyses of these minerals were determined with a 15 kV accelerating voltage, 50 nA current, and a 10 μm beam diameter. Peak counting times were 120 s for Ca, 60 s for Al, Fe and Mg, 50 s for Ti and Cr, and 40 s for Si, Mn, and Na. Backgrounds for all analyses were measured on each side of the peak for half the duration of the peak counting time. Calibration standards were Diopside-2 (UCLA) for Si and Ca; Sphene glass for Ti; Verma Garnet for Al, Fe, and Mn; Amelia Albite for Na; and Chromite (USNM 117075) for Mg and Cr. To monitor instrumental drift, the Diopside-2 and Jadeite standards were run after every thin section when analyzing pyroxene. The Verma Garnet and Chromite standards were run after every thin section when analyzing garnet. Only analyses within the range of 99.0–100.5 wt.% are used for geothermometer and geobarometer calculations.

4. Pyroxene and Garnet Mineral Analyses

Pyroxene and garnet mineral compositions were determined for six SLC garnet pyroxenites. The range in composition of minerals within each sample is narrow regardless of mode of occurrence (primary vs. exsolved) and thus averages are reported here (Tables S2–S4). Compositions along transects show only minor variability. For example, in a 400- μm -long transect from the core to the rim of a garnet grain in sample X02, all oxides varied by <0.4 wt.%. In addition, the numerous transects of FeO across adjacent cpx and gt minerals show no systematic compositional variation with distance from the grain boundary (Figure 3). Thus, the reported average composition of each mineral is representative of each sample and not an artificial composite composition.

The cpx in the six SLC garnet pyroxenites show similar Mg# (87.6–82.6 assuming no ferric iron, except for sample X20, 77.3; Table S2). Concentrations are moderate for CaO (18.2–19.9 wt.%), Al_2O_3 (6.1–7.1 wt.%), TiO_2 (0.7–1.2 wt.%) and Na_2O (1.5–2.4 wt.%) and low for Cr_2O_3 (0.02–0.34 wt.%). The opx in these samples have similar Mg# (88.3–83.5) except for sample X20 (79.4). The other oxides are moderate (Al_2O_3 , 4.3–5.3 wt.%), low (TiO_2 , 0.20–0.29 wt.%; CaO, 0.71–0.96 wt.%) or very low (Na_2O , 0.09–0.15 wt.%) for all but sample X20, which is anomalously high in TiO_2 (1.1 wt.%), Al_2O_3 (9.5 wt.%) and CaO (2.0 wt.%; Table S3).

Garnet compositions have relatively narrower compositional ranges for all oxides except for FeO and MgO in sample X20 (Table S4). Otherwise, in the six rocks the Al_2O_3 content is high (22.8–23.7 wt.%), CaO is

Figure 3. (a) FeO compositions versus distance from a grain boundary in adjacent garnet (gt) and clinopyroxene (cpx) grains in five samples (errors in both quantities approximately represented by symbol sizes). The number of FeO compositions plotted are equivalent to number of cpx-gt pairs used for geobarometer. (b) FeO normalized by the mean composition at distances $>50\ \mu\text{m}$ from the grain boundary for each gt or cpx grain. This plot shows that there is no systematic deviation from those mean values upon approaching the grain boundary that could be caused by diffusion near the boundary of differing composition, if the grains were not in chemical equilibrium (Müller et al., 2013).

moderate (5.0–5.3 wt.%), and TiO_2 and Cr_2O_3 are low (0.22–0.28 wt.%, 0.01–0.43 wt.%; Table S4). There is no compositional distinction for garnet between isolated grains versus those surrounded by spinel.

5. Geothermometry and Geobarometry

The pressure-temperature (P-T) conditions of the garnet pyroxenite xenoliths prior to being picked up by the ascending SLC magma were estimated using the two-pyroxene geothermometer of Putirka (2008) (modified in 2015, Putirka per. comm.) and the garnet-clinopyroxene geobarometer of Beyer et al. (2015). The two-pyroxene geothermometer requires major element compositions of cpx and opx pairs that are in contact with one another. At least 10 temperature calculations for different cpx and opx pairs with a variety of textures were made for each sample except sample X20, which has eight temperature calculations. The temperature calculations are based on Equation 36 of Putirka (2008). This equation requires that all cpx grains have an Mg# greater than 70, which is true for the six SLC xenoliths (Table S2; Table S6). The method includes a test for equilibrium based on Fe-Mg exchange, and we found that all but one cpx-opx pair from sample X20 fall within the equilibrium range ($K_D(\text{Fe-Mg}) = 1.09 \pm 0.14$). Initial calculated temperatures ranged from 955°C to 1040°C. The temperatures (and pressures) were updated by iterating between the geothermometer and geobarometer calculations as described below.

The garnet-clinopyroxene geobarometer (Beyer et al., 2015) requires: (1) a temperature estimate, (2) garnet end-member fractions (% almandine, % pyrope, and % grossular), and (3) cpx cation components. Also, the garnet and cpx grains for the calculations must be in contact. The temperature estimate comes from the two-pyroxene geothermometer. Garnet end-member percentages were calculated using major element compositions by normalizing the cations in the VIII site to 3 (i.e., $\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca} = 3$) after adjusting

the $\text{Fe}^{3+}/\text{Fe}^{2+}$ so that the positive charge is equal to 24 (to balance the negative charge from 12 oxygens). The “Goal Seek” function in Excel was utilized to arrive at the solution that satisfies both the normalization and the charge balance. Once satisfied, the spreadsheet provided garnet end-member percentages. Cpx cations were calculated assuming six oxygens per formula unit (Tables S7 and S8).

Uncertainties in determining the Ca-Tschermak fraction in the activity term in Equation 11 of Beyer et al. (2015) have the largest effect on pressure calculations from the garnet-cpx geobarometer. When Si concentrations in cpx are below 1.985 formula units, a 1% relative uncertainty on the SiO_2 analyses propagates to a maximum uncertainty of $\sim 10\%$ in pressure. Pressure uncertainties rise sharply for pyroxenes with ≥ 1.985 Si formula units (e.g., 25% uncertainty at ~ 1.995 Si formula units; Beyer et al., 2015). A 5% uncertainty on any other major oxide propagates to an absolute pressure uncertainty of < 1 kbar (Beyer et al., 2015). The Si formula units for the cpx grains in the SLC garnet pyroxenites analyzed here are < 1.90 . This significantly decreased the uncertainty of the pressures calculated. The geobarometer allows the Fe^{3+} of cpx to be input. When calculating pressures, we used 0%, 10%, 20%, and 30% Fe^{3+} and found the maximum difference between these Fe^{3+} values to be very minor (< 0.2 kbar). At least 15 pressure calculations were made for four samples; sample X17 has seven pressure calculations and sample X20 has only two pressure calculations. Initial calculated pressures ranged from 12 to 17 kbar (omitting sample X20).

The pressure estimates were then used in the two-pyroxene geothermometer to obtain revised temperatures, which were used to update the geobarometer calculation, and so forth. For the pressure calculation, we also tested the alternative geobarometer of Putirka (2008), which is based on the compositions of adjacent cpx and opx. This method, however, produced pressures less than those required for stability of garnet in pyroxenite (3–13 vs. 13–17 kbar; Table S6; Hirschmann & Stolper, 1996). The garnet-clinopyroxene geobarometer was used because it gave values within the garnet stability field. The cpx grains used for the two-pyroxene geothermometer that were in contact with opx grains were not always the same cpx grains used for the garnet-clinopyroxene geobarometer (because they were not in contact with garnet). Therefore, an average pressure of each sample from the garnet-clinopyroxene geobarometer was used as the new pressure input for the subsequent temperature estimate. This was a reasonable approach given the limited compositional variation and temperature range within each xenolith (15.7–18.0 kbar for sample SL2; Table S7 and S8). This approach yielded a maximum standard pressure deviation < 1 kbar for each sample. Subsequent iterations of computing pressure and then temperature was undertaken following the same procedures. After three iterations between the geothermometry and geobarometry calculations, the temperatures and pressures of the xenoliths converged to stable values with negligible changes ($< 1^\circ\text{C}$; < 0.05 kbar) with continued iteration.

The final temperatures are 1010°C – 1115°C and final pressures are 13.1–18.3 kbar (Figure 4, Table S5), which corresponds to depths of 45–55 km (Figure 5). These temperature and pressure ranges exclude xenolith X20 (see below). Variations in temperature and pressure within individual samples are relatively small (e.g., X17 has temperature and pressure ranges of 1048°C – 1065°C and 14.4–16.6 kbar), reflecting the tight compositional range measured within individual samples (see Supplement Tables). The homogeneous character of the individual grains is strong evidence for chemical equilibrium at the computed P-T conditions. A recent change in temperature for example, would be expressed as compositional gradients, especially near grain boundaries. We see no evidence of such gradients (Figure 3). The homogeneous nature of the relatively large ($\sim 100\ \mu\text{m}$) mineral grains is corroborating evidence for equilibrium conditions. Further confidence in the results is provided by the presence of both spinel and garnet in all the xenoliths, combined with the fact that the P-T estimates all straddle the spinel-garnet stability line (O'Neill, 1981; Figure 5).

Xenolith X20 was found to be problematic. At high magnification, very thin interstitial glass coating are visible on some minerals that were not noticed during petrographic examination. This sample had relatively few paired minerals of sufficient size to avoid secondary fluorescence issues, displays relatively large compositional heterogeneity, and yields pressures (7.1–7.8 kbar) and temperatures (984°C – 1004°C) that are much lower than those of the other xenoliths. We therefore do not consider the results for this sample in our final interpretations.

Figure 4. (a) and (b) Histograms of garnet pyroxenite xenolith temperatures using the two-pyroxene geothermometer (Putirka, 2008, revised in 2015, Putirka pers. comm.). (c) and (d) Histograms of garnet pyroxenite xenolith pressures using the garnet-clinopyroxene geobarometer (Beyer et al., 2015).

To further augment the information provided by the SLC xenoliths, we applied the two-pyroxene geothermometer and gt-cpx geobarometer on the mineral data for nine SLC garnet pyroxenites produced by Keshav et al. (2007) (Figure 5). Within a given garnet pyroxenite, there were many modes of occurrence for each mineral (host cpx, exsolved cpx in opx, cpx with no exsolution, etc.); therefore, one sample may have more than one temperature and pressure estimate. Compared to the results from our chemical analyses, the more variable compositions measured by Keshav et al. (2007) yield a significantly larger variation in pressure over a comparable range in temperature. The P-T conditions computed with Keshav et al. (2007) data overlap those computed from our data, reinforcing our results.

Our P-T range is somewhat cooler and lower pressure than those estimated by Sen (1988) who used early generation geothermobarometers (Ellis & Green, 1979; Wells, 1977). Other researchers proposed the SLC garnet pyroxenite xenoliths are high pressure (>20 kbar) crystal fractionates from alkali basalts (Bizimis et al., 2005; Frey, 1980; Keshav et al., 2007). The estimated pressures of >30 kbar reported by Keshav et al. (2007) were based on Milholland and Presnall (1998) liquidus phase relations and the assumption that olivine + cpx + garnet were in equilibrium with melt. Bizimis et al. (2005) estimated pressures of

Figure 5. Geotherms of (a) Parsons and Sclater (1977) and (b) Stein and Stein (1992) plate cooling models, for labeled seafloor ages. "Normal" lithosphere temperature for O'ahu would follow the 90-Myr geotherm (bold). Squares (colored as in Figure 4) mark median P-T calculations of our new samples, bars delimiting $\pm 1\sigma$. Blue circles show recalculated P and T for mineral data from Keshav et al. (2007). Spinel-garnet stability fields (O'Neill, 1981) are separated by the dashed red line. Depth is relative to the seafloor adjacent to the island where temperature is assumed to be at 0°C (consistent with the seafloor cooling models) but the relationship to pressure accounts for a volcano crust density of 2,800 kg/m³ extending from sea level to 18–19 km below sea level (Watts & ten Brink, 1989). The pyroxenite solidi of Pertermann and Hirschmann (2003) (blue line) and for a garnet-clinopyroxenite from Salt Lake Crater (Keshav et al., 2007, yellow circles with extrapolating dashed line) bound the solidi expected for our samples.

20–30 kbar using Brey and Köhler (1990) geobarometer and temperature estimates of 1100°C–1400°C, based on the Fe²⁺/Mg exchange between cpx and garnet (Ellis & Green, 1979; Ganguly et al., 1996; Krogh, 1988). Finally, lower temperatures were determined (Bizimis et al., 2013) using the method of Fe²⁺/Mg exchange between cpx and garnet, as well as the Ca-in-orthopyroxene and orthopyroxene-clinopyroxene Ca-Mg exchange thermometers (Brey & Köhler, 1990; Nimis & Grütter, 2010). The lower temperatures led to lower pressure estimates using the Al-in-opx thermobarometer of Brey and Köhler (1990) and Nickel and Green (1985) for the garnet-bearing samples. Our P-T estimates show good agreement with those of Bizimis et al. (2013).

6. Discussion

6.1. Origin and Thermal Equilibration of Xenoliths

Our P-T estimates can be interpreted in light of predicted geotherms for oceanic lithosphere (Figure 5). Two classic thermal models derived from observations of seafloor depth and heat flow are considered. Parsons and Sclater (1977) plate cooling model (PS77) represents a low-temperature end-member (Figure 5a); its absolute asthenospheric temperature of 1350°C is consistent with that of Priestley and McKenzie (2006) thermal model, derived from shear-wave velocities of the ocean basins. Stein and Stein (1992) plate cooling model (GDH1) represents a high-temperature end-member for normal lithosphere (Figure 5b); its asthenospheric temperature of 1450°C is more comparable to petrologic estimates of the liquidus temperatures of normal mid-ocean ridge basalt (e.g., Putirka et al., 2007).

Comparing our new P-T estimates with geotherms for a seafloor age of 90 Myr—the approximate age of the oceanic crust during O'ahu shield volcanism (e.g., Detrick & Crough, 1978; Pleus et al., 2020)—indicates that the xenoliths resided at much higher temperatures than expected for their associated pressures (Figure 5). The median temperatures are elevated by ~300°C and ~200°C compared to the PS77 and GDH1 models, respectively. Importantly, these temperature anomalies are at mid-lithosphere depths (45–55 km depth), shallower than the theoretical base of the lithospheric thermal boundary layer by 70–80 km for PS77 (plate thickness of 125 km) and 40–50 km for SS92 (plate thickness of 95 km).

Identifying the cause of the elevated temperatures requires consideration of the origin of the xenoliths. Evidence from Sr, Nd, Pb, and Hf isotope compositions of SLC garnet pyroxenites indicate that the xenoliths did not originate in Pacific upper mantle; instead, they were derived from the same source as the Honolulu

Figure 6. Cartoon of hypothesized situation of elevated temperatures (indicated by two arbitrary isotherms) due to heating primarily by magma that has penetrated the lithosphere during the shield (dark gray lines) and/or rejuvenated volcanic phases (dark and light red lines). Deeper heating is caused by the mantle plume. Dark green-to-orange indicates cool-to-hot. The lithospheric plate is flexing due to the load of the islands. The curvature of the plate is dominantly downward except below the very center of the islands where the plate has been weakened by the temperature anomaly. Arrows represent the *P* axes and *T* axes of earthquake focal mechanisms in the radial pattern found by Klein (2016) beneath Hawai'i Island.

Volcanics (Bizimis et al., 2005, 2013). The geochemical evidence supports the interpretation that the SLC xenoliths are cumulates of rejuvenated phase magma (e.g., Keshav et al., 2007). It is therefore likely that the SLC xenoliths crystallized within a magma channel carrying rejuvenated phase magma through the lithosphere.

To address the thermal state of the adjacent lithosphere, we first consider the conductive cooling timescale of such a magma channel. Reported widths of mafic dikes from active and fossil seafloor spreading centers are commonly ~ 1 m, whereas the largest mafic dikes in continental crust have widths of ~ 100 m (e.g., Qin & Buck, 2008). Magma channels (i.e., dunite veins) in the exhumed mantle section of ophiolites show similar width ranges (Kelemen et al., 2000). Assuming widths of $W_T = 1\text{--}100$ m and a thermal diffusivity of $D_T = 10^{-6}$ m²/s, the conductive cooling timescale is $\tau_T = (W_T)^2/D_T = 10^6\text{--}10^{10}$ s, or 0.03–300 years. In other words, after the garnet pyroxenites crystallized, they would have thermally equilibrated to the temperature of the surrounding lithosphere within weeks to a few 100 years.

Constraints on the timescale of chemical equilibrium are provided by the lack of spatial gradients in mineral composition as well as the relatively large size and compositional uniformity of the exsolved grains. At the relevant temperatures of 1000°C–1100°C, Fe-Mg interdiffusivities in garnet and cpx are $1\text{--}4 \times 10^{-19}$ m²/s and $1.5\text{--}15 \times 10^{-20}$ m²/s, respectively (Müller et al., 2013). In this temperature range, the diffusivity for opx closely follows that of garnet, and the diffusivities of Ca and Al are 1–2 orders of magnitude lower (Lierenfeld et al., 2019). A conservative estimate of the equilibrium timescale is computed if we assume a Fe-Mg interdiffusivity of $D_{\text{Fe-Mg}}$ of 10^{-19} m²/s and a length scale of $W_C = 100$ μ m for the size of exsolved grains or a minimal distance over which there are no compositional gradients. The resulting timescale is $\tau_T = (W_C)^2/D_{\text{Fe-Mg}} = 3,000$ years. Using $W_C = 400$ μ m, yields $\tau_T = 50,000$ years.

A simple explanation is that a rejuvenated magmatic event prior to that at SLC began penetrating the lithosphere and deposited the garnet pyroxenites at 45–55 km depth (Figures 5 and 6). Within weeks-to-hundreds of years, these rocks cooled by $\sim 200^\circ\text{C}$ from their solidus temperature to 1000°C–1100°C, and there they resided for $>3,000$ years to allow secondary grains to nucleate and exsolve, and for compositions in all of the grains to homogenize. The xenoliths were then delivered to the surface by SLC magmatism. The 550 kyr age contrast between the oldest (800 kyr) rejuvenated lavas on O'ahu and the SLC lavas (250 kyr; Ozawa et al., 2005) can be considered an upper-bound for the in situ residence time. That the xenoliths probably remained at or near 1000°C–1100°C for $10\text{--}10^5$ times longer than they took to cool from its solidus suggests that the surrounding lithosphere had been anomalously warm. We hypothesize that the lithosphere had been reheated by the action of the Hawaiian hotspot.

6.2. Geophysical Evidence, Mechanisms, and Consequences of Lithospheric Reheating

Seismic studies arising out of the PLUME ocean-bottom seismometer experiment provide independent evidence for substantial temperature anomalies within the lithosphere beneath the Hawaiian chain. The tomography models derived from surface-wave inversions (Laske et al., 2011) as well as a joint inversion of both body and surface waves (Cheng et al., 2015) show anomalously low S-wave speeds by as much as -4% at depths shallower than 50 km over lateral distance scales of 100–200 km. These anomalies suggest elevations in temperature by hundreds of degree Celsius (Priestley & McKenzie, 2006) at these shallow-to-mid-lithosphere depths, supporting the findings of this study.

Substantial reheating of the mid-lithosphere within the ~ 2 Myr time frame between the onset of Ko'olau shield volcanism, and the beginning of the Honolulu rejuvenated volcanic series, requires rapid and extreme shoaling of the local thermal boundary layer. Conductive heat transport from the hot mantle plume (Wolfe et al., 2009), alone, is too slow, so some form of advective heat transport is needed. Three-dimensional geodynamic models of a mantle plume interacting with the lithosphere predict that sublithospheric convection in the solid-state can advectively erode the base of the lithosphere, but heating at depths of < 50 km requires several millions of years longer (Bellas et al., 2020) than allowed by the history of rejuvenated volcanism on O'ahu.

The mechanism that is mostly likely to produce such a shallow thermal anomaly is heat carried by magma as it penetrates the lithosphere (e.g., Mittelstaedt et al., 2008). Magma penetrating during the rejuvenated phase of volcanism is one potential source of heat. Although this phase is very small in volume, it is distributed on the island scale. Probably the more significant heat source is the magma that penetrated the lithosphere during the much more voluminous shield-building phase of volcanism. The distances separating the center of the Ko'olau shield and SLC suggest that the magmatic heating can extend over a lateral area comparable to the footprint of a shield volcano. This lateral scale of magmatic heating is further supported by xenoliths from other (Kaaui-Pali-Kalihi) rejuvenated vents dispersed across the southern flank of the Ko'olau volcano and showing equilibrium P-T conditions consistent with excess lithospheric temperatures comparable to those in this study (Sen et al., 2005).

A temperature anomaly at these mid-lithosphere depths may impact the flexural response of the lithosphere due to the weight of the volcano chain. There are two primary issues. The first is that the flexural rigidity of the lithosphere along the Hawaiian chain appears significantly weaker than predicted by the relevant, laboratory-derived rheological laws and assuming a normal 90-Myr geotherm (Bellas et al., 2020; Pleus et al., 2020; Zhong & Watts, 2013). Given that it is unlikely that solid-state convection can induce such a shallow temperature anomaly, it was argued that the laboratory-derived rheologies are too strong, and thus require revision to lower strengths (Bellas et al., 2020; Zhong & Watts, 2013). Another study (Hunter & Watts, 2016), however, found that some of the same rheological laws successfully predicted the flexure of the lithosphere around the Pacific subduction zones, but required substantial weakening to adequately predict the flexure beneath Hawai'i. A plausible explanation for this inconsistency is that the rheological laws are not erroneous, but rather lithospheric temperatures are anomalously warm beneath the Hawaiian chain (Pleus et al., 2020), and not at Pacific subduction zones. The excess heat identified in this study could play a major role if it contributes to temperature anomalies of lateral dimensions (100–200 km) imaged by seismic tomography (Cheng et al., 2015; Laske et al., 2011). On the other hand, if magmatic heating is constrained to an area comparable to the footprint of an island (i.e., a length scale several times shorter than the dominant flexural wavelength), then the effects on the large-scale flexural response is questionable and would require testing.

The second issue regarding the impacts of magmatic heating on lithosphere flexure pertains to the pattern and types of earthquake focal mechanism beneath Hawai'i's Big Island (Klein, 2016). Earthquakes deeper than ~ 20 km show focal-mechanism *P* axes with a clear radial pattern around the central part of the island, indicating a corresponding pattern of deviatoric, horizontal compression in the deeper part of the brittle-elastic lithosphere (Figure 6). Earthquakes shallower than 20 km show focal mechanism *T* axes that tend to radiate from the island center, indicating a corresponding pattern of deviatoric, horizontal tension in the shallow part of the plate. This stress regime is expected if the lithosphere is flexed with a downward curvature around the island center. Such downward-only curvature is explained by the lithosphere beneath

the center of island being locally weakened by magma (Klein, 2016), analogous to the 2-D “broken plate” model (Watts & ten Brink, 1989).

7. Conclusions

We present new pyroxene and garnet compositions from a diverse suite of SLC garnet pyroxenite xenoliths, which prior studies have shown to have originally crystallized in the mantle from rejuvenated Hawaiian magmatism. Calculations using a revised geothermometer and a new geobarometer indicate that these rocks equilibrated at temperatures of 1000°C–1100°C and pressures of 13–18 kbar, corresponding to mid-lithospheric depths of 45–55 km. The temperatures at these depths are 200°C–300°C warmer than expected for normal lithosphere beneath 90-Myr-old seafloor. Our findings of remarkably homogeneous compositions within individual grains, no systematic compositional variation with distance from the grain boundaries of pertinent mineral pairs, and the presence of exsolved pyroxene and garnet hundreds of microns across indicate that the xenoliths record equilibrium P-T conditions with the surrounding lithosphere. The adjacent lithosphere was therefore anomalously warm (by 200°C–300°C), and inferred to have been reheated rapidly by magma as it penetrated the lithosphere during rejuvenated magmatism and the more voluminous shield stage of magmatism. Such magmatic heating is inferred to occur beneath all Hawaiian shield volcanoes. These hot and weak zones may reduce the effective flexural rigidity of the lithospheric plate as it buckles under the weight of the volcanoes, and may be reflected in the pattern of earthquake focal mechanisms beneath Hawai‘i’s Big Island.

Data Availability Statement

Sample metadata has been uploaded to the System for Earth Sample Registration (SESAR) and new data for this paper has been uploaded to EarthChem (<http://doi.org/10.26022/IEDA/111631>).

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References

- Beeson, M., & Jackson, E. D. (1970). Origin of garnet pyroxenite xenoliths at Salt Lake Crater, O‘ahu. In B. A. Morgan (Ed.), *Fiftieth anniversary symposia—Mineralogy and petrology of the upper mantle; sulfides; mineralogy and geochemistry of non-marine evaporites* (Vol. 3, pp. 95–112). Mineral. Soc. Amer. Spec. Pap.
- Bellas, A., Zhong, S., & Watts, A. (2020). Constraints on the rheology of the lithosphere from flexure of the Pacific plate at the Hawaiian Islands. *Geochemistry, Geophysics, Geosystems*, 21, e2019GC008819. <https://doi.org/10.1029/2019GC008819>
- Beyer, C., Frost, D. J., & Miyajima, N. (2015). Experimental calibration of a garnet-clinopyroxene geobarometer for mantle eclogites. *Contributions to Mineralogy and Petrology*, 169(2). <https://doi.org/10.1007/s00410-015-1113-z>
- Bizimis, M., Salters, V. J. M., Garcia, M. O., & Norman, M. D. (2013). The composition and distribution of the rejuvenated component across the Hawaiian plume: Hf-Nd-Sr-Pb isotope systematics of Ka‘ula lavas and pyroxenite xenoliths. *Geochemistry, Geophysics, Geosystems*, 14, 4458–4478. <https://doi.org/10.1002/ggge.20250>
- Bizimis, M., Sen, G., Salters, V. J. M., & Keshav, S. (2005). Hf-Nd-Sr isotope systematics of garnet pyroxenites from Salt Lake crater, O‘ahu, Hawai‘i: Evidence for a depleted component in Hawaiian volcanism. *Geochimica et Cosmochimica Acta*, 69, 2629–2646.
- Brey, G. P., & Köhler, T. (1990). Geothermobarometry in four-phase lherzolites II, New thermobarometers, and practical assessment of existing their barometers. *Journal of Petrology*, 31, 1353–1378. <http://doi.org/10.1016/j.jcrte.2007.10.012>
- Cheng, C., Allen, R. M., Porritt, R. W., & Ballmer, M. D. (2015). Seismic constraints on a double-layered asymmetric whole-mantle plume beneath Hawaii. In R. Carey, V. Cayol, M. Poland, & D. Weis (Eds.), *Hawaiian volcanoes: From source to surface, Geophysical Monograph 208* (pp. 13–24). Washington, DC: AGU, Jon Wiley & Sons, Inc.
- Clague, D. A. (1987). Hawaiian xenolith populations, magma supply rates, and development of magma chambers. *Bulletin of Volcanology*, 49, 577–587.
- Clague, D. A., & Dalrymple, G. B. (1987). The Hawaiian-Emperor volcanic chain, Part 1: Geologic evolution. *U. S. Geological Survey Professional Paper*, 1350, 5–54.
- Detrick, R. S., & Crough, S. T. (1978). Island subsidence, hot spots, and lithospheric thinning. *Journal of Geophysical Research*, 83, 1236–1244.
- Ellis, D. J., & Green, D. H. (1979). An experimental study of the effect of Ca upon garnet clinopyroxene Fe-Mg exchange equilibria. *Contributions to Mineralogy and Petrology*, 71, 13–22.
- Frey, F. A. (1980). The origin of pyroxenite and garnet pyroxenites from Salt Lake Crater, O‘ahu, Hawai‘i: Trace element evidence. *American Journal of Science*, 280A, 427–449.
- Ganguly, J., Cheng, W., & Tirone, M. (1996). Thermodynamics of aluminosilicate garnet solid solution: New experimental data, an optimized model, and thermometric applications. *Contributions to Mineralogy and Petrology*, 126(1–2), 137–151. <http://doi.org/10.1007/s004100050240>
- Hirschmann, M., & Stolper, E. (1996). A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB. *Contributions to Mineralogy and Petrology*, 124(2), 185–208.
- Hunter, J., & Watts, A. B. (2016). Gravity anomalies, flexure and mantle rheology seaward of circum-Pacific trenches. *Geophysical Journal International*, 207, 288–316.

- Kelemen, P. B., Braun, M., & Hirth, G. (2000). Spatial distribution of melt conduits in the mantle beneath oceanic spreading ridges: Observations from the Ingalls and Oman ophiolites. *Geochemistry, Geophysics, Geosystems*, 1(7). <https://doi.org/10.1029/1999gc000012>
- Keshav, S., Sen, G., & Presnall, D. C. (2007). Garnet-bearing xenoliths from Salt Lake Crater, O'ahu, Hawai'i: High-pressure fractional crystallization in the oceanic mantle. *Journal of Petrology*, 48, 1681–1724.
- Klein, F. W. (2016). Lithospheric flexure under the Hawaiian volcanic load: Internal stresses and a broken plate revealed by earthquakes. *Journal of Geophysical Research: Solid Earth*, 121, 2400–2428. <https://doi.org/10.1002/2015JB012746>
- Krogh, E. J. (1988). The garnet-clinopyroxene Fe-Mg geothermometer—A reinterpretation of existing experimental data. *Contributions to Mineralogy and Petrology*, 99(1), 44–48. <http://doi.org/10.1007/BF00399364>
- Laske, G., Markee, A., Orcutt, J. A., Wolfe, C. J., Collins, J. A., Solomon, S. C., et al. (2011). Asymmetric shallow mantle structure beneath the Hawaiian Swell—Evidence from Rayleigh waves recorded by the PLUME network. *Geophysical Journal International*, 187, 1725–1742.
- Lierenfeld, M. B., Zhong, X., Reusser, E., Kunze, K., Putlitz, B., & Ulmer, P. (2019). Species diffusion in clinopyroxene solid solution in the diopside-anorthite system. *Contributions to Mineralogy and Petrology*, 174(5). <https://doi.org/10.1007/s00410-019-1571-9>
- Milholland, C. S., & Presnall, D. C. (1998). Liquidus phase relations in the CaO-MgO-Al₂O₃-SiO₂ system at 3.0 GPa: The aluminous pyroxene thermal divide and high pressure fractionation of picritic and komatiitic magmas. *Journal of Petrology*, 39, 3–27.
- Mittelstaedt, E., Ito, G., & Behn, M. (2008). Mid-ocean ridge jumps associated with hotspot magmatism. *Earth and Planetary Science Letters*, 266, 256–270.
- Moore, W. B., Schubert, G., & Tackley, P. J. (1998). Three-dimensional simulations of plume lithosphere interaction at the Hawaiian swell. *Science*, 279, 1008–1011.
- Müller, T., Dohmen, R., Becker, H. W., ter Heege, J. H., & Chakraborty, S. (2013). Fe-Mg interdiffusion rates in clinopyroxene: Experimental data and implications for Fe-Mg exchange geothermometers. *Contributions to Mineralogy and Petrology*, 166, 1563–1576.
- Nickel, K. G., & Green, D. H. (1985). Empirical geothermobarometry for garnet peridotites and implications for the nature of the lithosphere, kimberlites and diamonds. *Earth and Planetary Science Letters*, 73, 158–170.
- Nimis, P., & Grütter, H. (2010). Internally consistent geothermometers for garnet peridotites and pyroxenites. *Contributions to Mineralogy and Petrology*, 159(3), 411–427.
- O'Neill, H. S. C. (1981). The transition between spinel lherzolite and garnet lherzolite, and its use as a Geobarometer. *Contributions to Mineralogy and Petrology*, 77, 185–194.
- Ozawa, A., Tagami, T., & Garcia, M. O. (2005). Unspiked K-Ar ages of Honolulu rejuvenated and Ko'olau shield volcanism on O'ahu, Hawaii. *Earth and Planetary Science Letters*, 232, 1–11.
- Parsons, B., & Sclater, J. G. (1977). An Analysis of the variation of ocean floor bathymetry and heat flow with age. *Journal of Geophysical Research*, 82, 803–827. <https://doi.org/10.1029/JB082i005p00803>
- Pertermann, M., & Hirschmann, M. M. (2003). Partial melting experiments on a MORB-like pyroxenite between 2 and 3 GPa: Constraints on the presence of pyroxenite in basalt source regions from solidus location and melting rate. *Journal of Geophysical Research: Solid Earth*, 108(B2). <https://doi.org/10.1029/2000jb000118>
- Pleus, A., Ito, G., Wessel, P., & Frazer, L. N. (2020). Rheology and thermal structure of the lithosphere beneath the Hawaiian Ridge inferred from gravity data and models of plate flexure. *Geophysical Journal International*, 222, 207–224. <https://doi.org/10.1093/gji/ggaa155>
- Priestley, K., & McKenzie, D. (2006). The thermal structure of the lithosphere from shear wave velocities. *Earth and Planetary Science Letters*, 244, 285–301.
- Putirka, K. (2008). Thermometers and barometers for volcanic systems. Minerals, inclusions and volcanic processes. In K. Putirka & F. Tepley (Eds.), *Reviews in mineralogy and geochemistry* (Vol. 69, pp. 61–120). Mineralogical Society of America.
- Putirka, K., Perfit, M., Ryerson, F. J., & Jackson, M. G. (2007). Ambient and excess mantle temperatures, olivine thermometry, and active vs. passive upwelling. *Chemical Geology*, 241, 177–206.
- Qin, R., & Buck, W. R. (2008). Why meter-wide dikes at oceanic spreading centers? *Earth and Planetary Science Letters*, 265, 466–474.
- Robinson, J., & Eakins, B. (2006). Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge. *Journal of Volcanology and Geothermal Research*, 151, 309–317. <https://doi.org/10.1016/j.jvolgeores.2005.07.033>
- Sen, G. (1988). Petrogenesis of spinel lherzolite and pyroxenite-suite xenoliths from the Ko'olau shield, O'ahu, Hawai'i: Implications for the petrology of the post eruptive lithosphere beneath O'ahu. *Contributions to Mineralogy and Petrology*, 100, 61–91.
- Sen, G., Keshav, S., & Bizimis, M. (2005). Hawaiian mantle xenoliths and magmas: Composition and thermal structure of the lithosphere. *American Mineralogist*, 90, 871–887.
- Stein, C., & Stein, S. (1992). A model for the global variation in oceanic depth and heat flow with lithospheric age. *Nature*, 359, 123–129.
- Watts, A., & ten Brink, U. (1989). Crustal structure, flexure, and subsidence history of the Hawaiian Islands. *Journal of Geophysical Research*, 94, 10473–10500.
- Wells, P. R. A. (1977). Pyroxene thermometry in simple and complex systems. *Contributions to Mineralogy and Petrology*, 62(2), 129–139.
- Wolfe, C. J., Solomon, S. C., Laske, G., Collins, J. A., Detrick, R. S., Orcutt, J. A., et al. (2009). Mantle shear-wave velocity structure beneath the Hawaiian hot spot. *Science*, 326, 1388–1390.
- Zhong, S., & Watts, A. B. (2013). Lithospheric deformation induced by loading of the Hawaiian Islands and its implications for mantle rheology. *Journal of Geophysical Research: Solid Earth*, 118(11), 6025–6048. <https://doi.org/10.1002/2013jb010408>