**Depths in a day - A new era of rapid-response Raman-based barometry using fluid inclusions.**

Running title: Depths in a day – a new era of rapid response barometry

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Word count: Abstract 70 (250 max), Main1705 (4000 including captions, excluding abstract, acknowledgments amd refs; 4 figs)

**Abstract (250 max)**

Rapid-response petrological monitoring is a major advance for volcano observatories to build and validate models of the plumbing systems that supply eruptions in near-real-time. A recent survey of volcano observatories identified the depth of the magmatic plumbing system as a high priority piece of information, but one that is currently not obtained on timescales relevant to eruption response (Re et al. 2021). To address this deficiency in petrological monitoring, we perform a rapid response simulation using tephra from the September 2023 eruption of Kīlauea. We show that Raman analyses of fluid inclusions can robustly determine magma reservoir depths within a day of receiving samples - a transformative timescale for decision making that has not previously been achieved by petrological methods. Fluid inclusion barometry has the most potential as a petrological monitoring tool in systems where the exsolved fluid phase has a high molar proportion of CO2, and a low molar proportion of H2O (XH2O). We compile published melt inclusion data and calculate the fluid composition at the point of vapour saturation. This compilation demonstrates that fluid inclusions are a robust method at many of the world’s most active and hazardous volcanic systems (e.g. Iceland, Hawai’i, Galápagos, East African Rift, Réunion, Canary Islands, Azores, Cabo Verde).

**Keywords:** Fluid Inclusions; Geobarometry; Raman Spectroscopy; Rapid Response; Volcano Monitoring

## **Introduction**

Volcano observatories increasingly use data collected from erupted lava and tephra samples in near-real-time to obtain information about the magmatic plumbing system to help inform decision-making during volcanic crises (Gansecki *et al.*, 2019; Re *et al.*, 2021; Pankhurst *et al.*, 2022). Most work so far has focused on the chemistry of erupted lavas and crystal cargoes (Pankhurst *et al.*, 2022) to gain insight into changing melt composition and rheological properties (e.g., Gansecki *et al.*, 2019). However, up until now, petrological monitoring has been unable to address the high-priority question– *Where is the magma coming from?* (Re *et al.*, 2021). At well-monitored volcanoes, such information can be used to draw analogies to previous eruptive episodes associated with specific storage reservoirs (e.g., vigour, pathway, or length of eruption), and to help interpret geophysical signals of ongoing activity. At poorly-monitored volcanoes, where there may be no prior constraints on magma storage geometry (Wieser *et al.*, 2023b), depths of storage are a vital parameter to begin interpreting unrest associated with a new episode of eruptive activity (Pritchard *et al.*, 2019) . Melt inclusion (MI) barometry, a widely popular petrological method to determine storage depths from volatile contents, takes months to years to complete (Re *et al.*, 2021). While mineral barometry can be implemented faster than melt inclusion measurements (only requiring electron probe microanalysis (EPMA) measurements on eruptive minerals), it is imprecise (Wieser *et al.*, 2023a), and therefore would only be able to constrain magma storage to very broad regions of the crust (e.g., stored in the crust vs. below the Moho). Mineral thermobarometry also has poor applicability at active volcanoes such as Kīlauea or Mauna Loa where the only major silicate phase in most lavas is olivine, the chemistry of which is not pressure sensitive, and where a precision of 1–2 km is needed to distinguish between storage reservoirs (Baker and Amelung, 2012; Anderson and Poland, 2016).

Recent developments have shown that Raman-based barometry of CO2-rich fluid inclusions (FI) provides an alternative to popular petrological barometers, with much smaller uncertainties than mineral barometry, and requiring far less time and resources than MI analyses (Dayton *et al.*, 2023; DeVitre and Wieser, 2024). This method uses spectral features of CO2 fluids to calculate a CO2 density using an instrument specific calibration (DeVitre *et al.*, 2021). Along with an estimate of entrapment temperature, this density is converted into an entrapment pressure using a CO2 Equation of State (EOS, Fig. 1). One major advantage of this method is that the conversion of CO2 density to pressure is relatively insensitive to the choice of entrapment temperature, a parameter which may not be known at the onset of a new eruptive episode (Fig. 1a-b). If we perform EOS calculations using the lower and upper limit of liquidus temperatures for olivine-saturated melts erupted at Kīlauea volcano throughout its history (~1100 and 1350 ˚C; DeVitre and Wieser, 2024), the change in pressure is at most ~20 %, which corresponds to ~0.2 – 0.4 km at depths representative of the shallower Halemaʻumaʻu reservoir (1-2 km), and ~0.6-1 km at the depths of the deeper south Caldera reservoir (3-5 km, Fig. 1b and Fig. S2-S5). These errors are of similar magnitude to those associated with the conversion of pressures to depths through an estimate of crustal density (an issue affecting all petrological barometers).

A number of recent studies have speculated that fluid inclusion barometry can be performed quickly enough to be useful for near real-time volcano monitoring (e.g., Dayton *et al.*, 2023; Zanon *et al.*, 2024). However, until now, there has been no rigorous assessment of just how quickly FI depths can be obtained from erupted material, and whether these timescales are short enough to have utility as a petrological monitoring tool. Performing these stress tests of methodologies during relatively small eruptions (as here) or as hypothetical simulations (e.g., Andrews *et al.*, 2019) are vital to ensure we are as prepared as possible for the next large volcanic crisis (Dietterich and Neal, 2022).

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**Figure 1. Temperature and X**H2O **sensitivity of the EOS method for** CO2**-rich fluid inclusion barometry.** (a) CO2 density vs Pressure for different magmatically relevant entrapment temperatures at Kīlauea using the EOS of Span and Wagner (1996). 1100 and 1350 ˚C are the lower and upper limit of liquidus temperatures for olivine-saturated melts erupted at Kīlauea volcano throughout its history. 1150 ˚C was our initial fixed temperature for days 1 and 2, 1240 ˚C is the rounded mean and median of all measured temperatures in our final dataset. (b) Close-up of panel a. Grey boxes show the depth range of Kīlauea magma storage – HM for Halema’uma’u reservoir and SC for South Caldera reservoir – inferred from FI and MI barometry as well as geophysics (DeVitre and Wieser, 2024; Lerner *et al.*, 2024). Stars show hypothetical FI trapped at HM and SC reservoirs with our initial guessed temperature (1150 ˚C) and error bars representing 1σ uncertainty from MonteCarlo simulations using a temperature uncertainty of ±125 ˚C (). (c) CO2 density vs Pressure at 1150 ˚C for various molar proportions of H2O in the exsolved fluid phase (XH2O) using the mixed H2O-CO2 EOS of Duan and Zhang (2006). Note that a small discontinuity is observed at 200 MPa due to parameter values being switched at this pressure (Yoshimura, 2023). (d) Close-up of panel c. Stars show hypothetical FI trapped at HM and SC reservoirs with our initial guessed temperature (1150 ˚C), XH2O inferred from the 2018 LERZ MI XH2O-P relationship from DeVitre and Wieser (2024) and error bars representing 1σ uncertainty from MonteCarlo simulations using an XH2O uncertainty of ±0.1 based on the maximum range of XH2O inferred in our dataset () when calculated using the upper limit XH2O-P relationship for Kīlauea from DeVitre and Wieser (2024).

## **Timeline of Rapid Response Simulation**

The eruption onset of Kīlauea volcano on September 10, 2023 provided an unprecedented opportunity to test the validity and speed of the fluid inclusion method, given that depths of the two main magma storage regions (Halemaʻumaʻu – HM at 1-2 km and South Caldera – SC at 3-5 km) at this volcano have been well constrained by various independent geophysical and petrological methods, including prior FI barometry (DeVitre and Wieser, 2024, Lerner et al. 2024).

Tephra samples representing the first ~14 hours of the September 2023 eruption were collected by Hawaiian Volcano Observatory (HVO) geologists on September 12 and mailed to UC Berkeley on September 15th (Fig. 2).

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**Figure 2. Workflow of the study, all times on this figure are Pacific Standard Time (PST).** Stick people show the contribution of individual team members, to indicate the total time associated with each step. We note that AB was trained in these procedures during the simulation and all reports were sent to HVO prior to 5:30 pm Hawaii Standard Time (HST), thus allowing for decision making for the following day.

Our simulation started on September 20 at 9 am PST (Day 1), the morning after sample receipt (Fig. 2). We used a production-line style workflow involving two undergraduates, a 1st year graduate student, a post-doc, and an assistant professor, with stations for crushing and sieving, mineral picking, FI preparation, sample cataloguing, and analysis. The first steps were to crush and sieve tephra, pick olivine crystals (size fractions 0.5-1 and 1-2 mm) crystals, and begin mounting crystals in CrystalBondTM\* to search for FI. By 2 pm PST (5 hrs into the simulation), we had collected our first Raman spectra. By ~7 pm PST, we had processed the spectra from 16 FI to get CO2 densities using a calibration based on the relationship between CO2 density and Fermi diad splitting distance (DeVitre *et al.*, 2021; DeVitre and Wieser, 2024). CO2 densities were converted into pressures using the pure CO2 EOS of (Span and Wagner, 1996). At the time of our simulation, EOS calculations considering the possible presence of H2O in the exsolved fluid were not easy to perform because of a lack of publicly available software tools to perform such calculations on modern operating systems. However, recent work by Yoshimura, (2023) identifying errors in the published equations for the H2O-CO2 EOS of Duan and Zhang (2006) means that calculations using mixed CO2-H2O EOS calculations can be now be performed in DiadFit as quickly as calculations involving the pure CO2 EOS. Using estimates of XH2O from previously published melt inclusion data at Kīlauea (Wieser et al. 2021, DeVitre and Wieser, 2024), calculated pressures would be ~10% higher than originally reported to HVO if the CO2-H2O EOS had been used instead (Fig. 3 arrows, Fig SX in supplementary materials). This slight difference is not sufficient to affect the interpretation of our results, as the shift is far smaller than the pressure offset between the HMM and SC reservoir.

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**Figure 3. Evolution of results over 4 days.** a) Schematic model of Kīlauea’s plumbing system, indicating reservoir depths determined by geophysics and prior petrological work (HMM- Halemaʻumaʻu; SC – South Caldera). b) By the end of Day 1, FI revealed that the crystals were supplied from depths consistent with the Halemaʻumaʻu reservoir. Kolmogorov-Smirnov tests show that September 2023 FI are recording depths significantly shallower than those recorded by FI (critical D = 0.22, stat = 0.24, pval=0.016) and MI (critical D = 0.22, stat = 0.41, pval=3.51e-06) from the 2018 lower East Rift Zone eruption, which required a contribution from the South Caldera reservoir. 1 Melt inclusion data for the 2018 LERZ eruption is from Wieser *et al.*, (2021); 2 Fluid inclusion data for the 2018 LERZ eruption is from DeVitre and Wieser, (2024) c) By the end of Day 2, depths from 46 FI were sent to HVO, confirming a dominant role of the Halemaʻumaʻu reservoir. On Day 2 we applied a conservative degassing filter (SO2/CO2 peak ratio < 0.1). d) By the end of Day 4, after taking a mean of repeated analyses of single FI, applying more stringent data filters, using FI-specific temperatures, and a more appropriate crustal model (density of ~2300 kg/m3 with a normal error distribution of 100 kg/m3), entrapment depths with uncertainties were linked to crystal chemistry. Data from Day 4 was also filtered using an SO2/CO2 peak ratio < 0.22. Error bars correspond to uncertainties propagated using Monte Carlo simulations (see Supplementary Information S1 Appendix). Olivine Fo equilibrium field is calculated based on Glass EPMA data collected on September 11, 2023 (see Supplementary Information S1 Appendix). We also show the effect of H2O corrections on pressures recalculated using XH2O inferred from MI data (Wieser *et al.*, 2021; DeVitre and Wieser, 2024). We note here that initial data for Days 1 and 2 did not filter out repeated analyses (1 repeated FI in Day 1 and 6 in Day 2), pressures were calculated using an estimated entrapment temperature of 1150˚C (Wieser *et al.*, 2021; DeVitre and Wieser, 2024), and depth was calculated using the model of (Ryan, 1987) described in (Lerner *et al.*, 2021) for crustal density.

For the first and second days prior to acquisition of Energy Dispersive Spectroscopy (EDS) data, we assumed an entrapment temperature of 1150 ˚C for all FI, based on geothermometric estimates of erupted liquids for previous events such as the 2018 LERZ eruption (Gansecki *et al.*, 2019; DeVitre and Wieser, 2024). On day 4, we calculate entrapment temperatures for each FI using the host forsterite content measured by EDS (DeVitre and Wieser, 2024), yielding temperatures spanning 1182–1307 ˚C. Thus, the average error induced by our initial assumption of 1150 ˚C is only ~7% (with a maximum offset of only 12 %). While crystallization temperatures at Kīlauea are relatively well constrained relative to other volcanic systems, using similar regression methods to those employed by DeVitre and Wieser, (2024) relating liquid compositions to host olivine contents, it should always be possible to constrain temperatures within ~100 K at different volcanic systems using host mineral chemistry.

On days 1 and 2, pressures were converted into depths using the crustal density model of Ryan, (1987) parameterized by Lerner *et al.* (2021). We shared the resulting histogram (Fig. 3a-b) of storage depths with HVO collaborators showing that crystals, and thus magma, were likely coming from the shallower Halemaʻumaʻu reservoir of Kīlauea (HMM on Fig. 3a-b). It worthwhile to note that the number of FI reported on Day 1 is comparable to many melt inclusion studies, which often aim for ~20 MI per sample but frequently report fewer. For example, Lerner *et al.* (2021) reported only 8 MI from the 2018 eruption with sufficient data to calculate saturation pressures (we count MI with glass Major Element contents, H2O contents and total CO2 contents (no bubble MI, bubble+glass, including glass below detection limit)) and Aster *et al.*, (2016) reported 13 MI with sufficient data.

We also had an additional ~20 FI fully prepared and catalogued for analysis by the end of Day 1. On Day 2, these 20 FI were analysed, while additional FI were prepared and catalogued. After analysis of ~15 crystals hosting FI, these crystals removed from CrystalBondTM and placed on tape to make an epoxy mount. Epoxy was poured at the end of Day 2. By ~8:30 pm PST on Day 2, we shared an updated histogram of 46 FI pressures and depths from 28 crystals, confirming the dominant contribution of the Halemaʻumaʻu reservoir (Fig. 3a and c). On Day 3, while waiting for the epoxy to fully set, we finished analysing the remaining prepared FI. Then we polished the mount and began cataloguing the regions of crystals which were closest to each FI on which to perform EDS analyses. On Day 4, olivine forsterite contents (Fo = 100\*Mg/(Mg+Fe) molar) were determined by EDS, providing a framework to further interpret the plumbing system (Fig. 3d). The Fo content of an olivine is a function of MgO and FeO in the liquid and the Ol-Liq partitioning coefficient (KD). Thus, the Fo contents of the host olivine close to each FI can be used to assess the calculated storage depth in its broader petrographic context (e.g., distinguishing high-Fo olivines which crystallize from more primitive melts from low Fo olivines forming in more evolved melts). This olivine forsterite content can also be used to estimate the likely entrapment temperature of each fluid inclusion (see DeVitre and Wieser, 2024) for performing EOS calculations, rather than having to use a uniform temperature as on Day 1-2. We recalculated all FI pressures on Day 4 using fluid inclusion specific entrapment temperatures from our EDS data.

Our results clearly show that the majority of FI were entrapped at ~1–2 km below the surface (Fig. 3d), which aligns well with the depths of the Halemaʻumaʻu reservoir interpreted from geophysics (Baker and Amelung, 2012; Anderson and Poland, 2016; Anderson *et al.*, 2019), MI barometry (Lerner *et al.*, 2021; Wieser *et al.*, 2021), and FI barometry (DeVitre and Wieser, 2024; Lerner *et al.*, 2024). While the greater number of analyses from data processed on Day 2 and Day 4 certainly enhance the story, it is notable that depths calculated on Day 1 fall within final proposed storage reservoir depths. Rapid EDS analyses of olivine Fo contents close to each FI reveal that olivine crystals grew from a wide range of melt compositions. It is interesting to note that FI in the cores of high-Fo (e.g., >86) olivine crystals return pressures indicative of the shallower Halemaʻumaʻu reservoir, given that it has been suggested based on previous eruptions that these high-Fo olivine crystals predominantly grow in the deeper South Caldera reservoir (SC on Fig. 3a) where high MgO melts are thought to reside (Helz *et al.*, 2014; Pietruszka *et al.*, 2015, 2018; Wieser *et al.*, 2019; Lerner *et al.*, 2024). We suggest three possible scenarios to explain the relatively shallow pressures documented in high-Fo olivine crystals:

1) FI in high-Fo olivine crystals were entrapped within the South Caldera reservoir and then transported into the Halemaʻumaʻu reservoir, where the FI re-equilibrated to lower pressures prior to eruption over shorter timescales than would be required to reset the host Fo content.

2) High-MgO melts were injected into the Halemaʻumaʻu reservoir, where high-Fo olivine crystallized and trapped FI at shallow depths (Lerner *et al.*, 2024).

3) Complex skeletal growth of olivine crystals during extensive undercooling (e.g., Welsch *et al.*, (2013) could mean that high-Fo olivine cores which initially grew in the SC reservoir texturally evolved and trapped lower pressure FI in the Halemaʻumaʻu reservoir.

We think that scenario 1 is unlikely given the that FI from the 2018 lower East Rift Zone eruption appear not to have re-equilibrated despite stalling in the Halemaʻumaʻu reservoir for up to 2 years (DeVitre and Wieser, 2024; Mourey *et al.*, 2023), and our models of FI re-equilibration indicate <10% change in pressure over this time period. Current data does not allow us to resolve scenario 2 vs 3, but this eruption could provide an opportunity to explore this further, such as through detailed Phosphorous mapping in olivine around FI (as performed for melt inclusions by Esposito *et al.*, 2023). Regardless of the exact mechanism, our FI pressures indicate that erupted crystal cargo experienced storage at Halemaʻumaʻu reservoir depths prior to eruption, and thus this was the most probable reservoir supplying magma to the surface in the Sept 2023 eruption.

Br**oader applicability of the method**

Use of a pure CO2 EOS results in an underestimate of the entrapment pressure of fluid inclusions if there was H2O in the fluid at the time of inclusion entrapment (Fig. 3). At Kīlauea, melt inclusion data indicates that the exsolved fluid phase is ~90% CO2 at pressures corresponding to the HMM reservoir, and >95% CO2 at pressures indicative of the SC reservoir (Wieser *et al.*, 2021; DeVitre and Wieser, 2024). As discussed above, the effect of XH2O is small on calculated pressures presented here (Fig. 3d). However, to assess the utility of the fluid inclusion method for rapid-response petrology globally, it is necessary to evaluate XH2O contents, and the effect on calculated pressures from fluid inclusions.

We compiled melt inclusion suites from all over the world and different tectonic settings (Fig 4), calculating XH2O using MagmaSat (Ghiorso and Gualda, 2015), implemented in VESIcal (Iacovino *et al.*, 2021). We show the distribution, median and first and third quantiles of calculated XH2O for 4125 melt inclusions with SiO2<57 wt% on Fig 4b-c, coloured by tectonic setting. For each volcano, there is a clear correlation between XH2O and pressure with XH2O values taking an uptick to very high values at shallow pressures (Supporting Fig. S9a-i) as melt inclusions are trapped during enhanced degassing of H2O upon ascent. Thus, in this compilation, the median and first and third quantiles are likely most representative of XH2O in the main magma storage region. We stress the importance of considering XH2O when determining the suitability of this method to a particular system given that the XH2O pressure correction tends to be more significant at higher entrapment pressures. For example, if we consider an XH2O of 0.1 (the median XH2O of our FI dataset at Kīlauea and a commonly assumed XH2O in deep storage systems), the pressure correction goes from <15% at pressures < 220 MPa (~10 km) to ~20% at 700 MPa (~30 km). Naturally, the correction is even more significant if XH2O is greater than 0.1 (e.g., 25-30% at P<150 MPa and ~50% at P = 700 MPa for XH2O=0.2; Fig 1). We plot on Fig 4a the median XH2O for magmas with SiO2 <57 wt% around the world.

It is also noteworthy that the vast majority of melt inclusion suites in this compilation did not measure CO2 in the vapour bubble, meaning that the total CO2 content of the inclusion has been underestimated, and XH2O overestimated. This can be demonstrated by comparing XH2O values at volcanoes where there some studies with Raman measurements and some without (Supporting Fig. S9c EAR, Fig. S9h Kamchatka and Cascades). Thus, Fig. 4c shows a compilation only using melt inclusions where bubble CO2 was accounted for by Raman spectroscopy.

Both compilations demonstrate that subduction zones record much higher XH2O globally than Mid-Ocean Ridge basalts, ocean island basalts, continental rifts and intraplate volcanoes. It is also interesting that within hotspot and intraplate settings, regions with tholeiitic compositions (e.g. Iceland, Hawaii, Galapagos, Reunion, Deccan Traps) generally have lower XH2O values than regions with more alkaline magmas (e.g., Canary Islands, Azores, Cabo Verde, Supporting Fig. S9). This likely represents the lower melt extents in alkaline settings, and the possibility of more volatile-rich sources (e.g.,DeVitre *et al.* (2023)).

Thus, while rapid response fluid inclusion barometry is highly applicable to active volcanic regions such as Hawaii, Iceland, East African Rift (EAR), Reunion, Cabo Verde, and the Canary Islands, it is not appropriate in subduction zones such as Alaska, Kamchatka, Central America. Interestingly, although there is only a single study with Raman data in the Cascade arc (Aster *et al.*, 2016), it is noteworthy that the highest pressure inclusions have XH2O values <0.2. This may indicate that in dryer subduction zones such as the Cascades, fluid inclusions may have some utility for the most mafic, CO2-rich magmas.

To increase the accuracy of rapid-response petrological monitoring during future eruptions, it should be a priority to perform melt inclusion studies accounting for vapour bubble CO2 to determine approximate trends in XH2O-pressure space for a given volcanic system or region during times of quescience. This will allow assessment of the suitability of the fluid inclusion method, and permit appropriate corrections for the complexities of mixed fluids without requiring melt inclusion work during each eruptive episode. In systems with no prior constraints, our observations of correlations between alkalinity and XH2O can provide a first order assessment of appropriate XH2O values to use. We note that once arc magmas are excluded from the compilation, even if XH2O is entirely unconstrained, fluid inclusion barometry is still more accurate than other methods such as mineral-melt thermobarometry.

A map of the world with different colored lines

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Figure 4. Global compilation of XH2O in the exsolved fluid phase from melt inclusion data for Continental Rift, Intraplate, Mid-Ocean Ridge and Subduction Zone volcanoes (details and references in the supplement). Data is filtered to SiO2 < 57 wt% and Saturation Pressure >20 MPa (supplement for details). (a) World map coloured by Median XH2O of the melt inclusion suites, circles indicate Glass-only MI data and stars those for which CO2 has been constrained by Raman. (b) Boxplot of XH2O for melt inclusion suites plotted on panel a. Boxplots show the median, Q1 (25th quartile), Q3 (75th quartile) and whiskers mark the last datapoint before Q3+1.5\* (Q3-Q1) and the first datapoint after Q1-1.5\*(Q3-Q1). Violin plots show the density distribution of all the data and are coloured according to tectonic setting. (c) Boxplot of XH2O showing only MI suites which constrained Total CO2 by Raman spectroscopy. EAR – East African Rift, GSC - Galápagos Spreading Center, NAR – North Atlantic Ridge, JdFR – Juan de Fuca Ridge, GR – Gakkel Ridge, EPR – East Pacific Rise, MAR – Mid-Atlantic Ridge.

Lessons learned during the simulation

Rapid response simulations are vital to identify and resolve bottlenecks (yellow stars, Fig, 1, see Supplementary Information S1 Appendix for further details), allowing determination of critical magmatic system parameters more quickly in future volcanic crises. For example, we learnt that no courier services ship packages out of Hilo, Hawaiʻi over the weekend, and estimated delivery days were not reliable. In a true crisis, samples could be obtained within ~12 hours by getting someone to fly the samples from Hilo to San Fransisco on a direct flight. Our epoxy also took 18 hours to cure enough for polishing vs. 8 hours on the datasheet. We will work on identifying and testing faster curing epoxies to eliminate this delay. Finally, we spent significant time cataloguing samples on a research-grade microscope to help navigate on the Raman microscope, but later realized that smartphone cameras with teaching microscopes would have worked faster, as the person who found the inclusion could catalog it immediately. In the next eruptive crisis, eliminating these bottlenecks, implementing overnight shift work, and obtaining teaching release and class absences for students would allow magma storage depths to be determined on even shorter timescales.

Conclusion

This simulation shows that magma storage depths can be determined within a day of receiving samples, with modest resources and personnel requirements (e.g. no overnight shift work, with normal semester teaching and class schedules). For example, sample preparation was carried out using transmitted-reflected light microscopes from the University of California teaching collection, only using a research-grade microscope for sample cataloguing. Raman spectrometers are widely available at many universities, given that it is a popular technique in many other fields, such as material sciences, physics, chemistry, and biology, and the W-filament SEM used for EDS analyses to get olivine Fo contents has been around for 15 years (See Supplementary Information S1 Appendix).

Our global compilation of XH2Ovalues shows that Raman-based FI barometry has utility as a rapid-response petrological monitoring method at many of the worlds most active and hazardous basaltic volcanoes (e.g., Galápagos, Réunion, Azores, Canary Islands, Iceland, Cabo Verde). As our understanding of exsolved fluid compositions improves as more studies account for CO2 held within vapour bubbles, it is likely that the applicability of this method may expand to even more volcanic systems (e.g. to dryer arc magmas such as those found in the Cascades). This technique adds valuable quantitative storage depth information that expands on HVO’s routine near-real-time chemical monitoring with bulk rock ED-XRF(Gansecki *et al.*, 2019).

{ This is HVO people’s additional paragraph – not super sure where to fit it }

Rapid-response quantification of magma source depths provides a key advancement for volcano observatories that utilize near-real-time geochemical monitoring to better understand eruptions as they unfold (see Re et al., 2021 overview; Hawai‘i–Gansecki et al., 2019; La Palma–Pankhurst et al., 2022; Fuego–Liu et al., 2020; Italy–Corsaro and Miraglia, 2022). The return of eruptive activity at Kīlauea in 2020 was accompanied by many questions about how the magmatic plumbing system had changed following the summit collapse in 2018 (Lynn et al., 2024) and FI barometry would have been a critical addition to understanding the eruption and the system. Utilizing a low-hazard eruption from a well-understood volcano (e.g., September 2023 Halema‘uma‘u eruption of Kīlauea) was a key component of testing our rapid-response application, as this scenario was not taxing on observatory staff or detracting from their primary response goals of keeping communities informed of any evolving hazards. Furthermore, this study is a clear example of identifying key science questions and pre-planning science activities to facilitate more rapid implementation across a broader scientific group, a specific recommendation made by the CONVERSE Hawai‘i Scientific Advisory Committee (Cooper et al., 2023) as a result of coordination experiences for Hawaiian eruptions.

**Author contributions**

Author contributions for lab work are shown on Fig. 2. CD and PW wrote the paper. CD, PW, AR, BR, and AB prepared tephra, picked olivine, found Fis, catalogued them, mounted them, and conducted Raman analyses. CD and PW performed all spectral fitting, data processing, and figure making, with schematic cartoons shown in Fig. 2 from AB. JG developed the Mg/Fe calibration for the EDS detector and MG performed EDS analyses with help from JG. KJL, DTD, NID and KMM collected samples, processed them in Hilo, and provided eruption context. KJL and DD prepared the glass mount and did the EMPA glass analyses.

**Acknowledgements**

PW and CD acknowledge support from NSF EAR 2217371 and the Berkeley Rose Hills Innovator Program. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

**Data availability**

All data are made available in the Supplementary Information associated with the publication. We include detailed materials and methods (S1 Appendix), complete processed Dataset (S2 Dataset), a compilation of microphotographs of the FI and crystals (S3 FI Image Compilation) and a record of emails reporting results to HVO and tracking receipts related to sample shipment (S4 Email and tracking record). All raw data and Jupyter notebooks are also stored on Github (<https://github>.com/cljdevitre/2023\_Kilauea-rapid-response-simulation). The Github repository will be archived on Zenodo upon acceptance.

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