**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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**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 (). 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). For example, 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).

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, this is the first study to rigorously assess 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. The CONVERSE Hawai‘i Scientific Advisory Committee (Cooper *et al.*, 2023) specifically recommended that key science questions should be identified, and pre-planning science activities performed, to facilitate more rapid implementation across a broader scientific group during hazardous eruptions. Performing these simulations during relatively small, low hazard eruptions (as here) or as hypothetical simulations (e.g., Andrews *et al.*, 2019) are vital to ensure that any bottle necks are ironed out so that we are as prepared as possible for the next large volcanic crisis (Dietterich and Neal, 2022). Importantly, this simulation revealed that rapid response fluid inclusion work in collaboration with academic institutions was not taxing on observatory staff and thus that this method can be employed during future eruptions.

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***Figure 1. Sensitivity of the fluid inclusion barometry to Temperature and*** *(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 the temperature used for EOS calculations during day 1 and 2 of the simulation, 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 inferred from FI and MI barometry as well as geophysics (DeVitre and Wieser, 2024; Lerner et al., 2024). HMM= Halema’uma’u reservoir, SC = South Caldera reservoir. Stars show hypothetical FI trapped at HMM and SC reservoirs with our initial guessed temperature (1150 ˚C) and error bars representing 1σ uncertainty from Monte Carlo 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 () 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 HMM and SC reservoirs with our initial guessed temperature (1150 ˚C), inferred from the 2018 LERZ MI -P relationship from DeVitre and Wieser (2024) and error bars representing 1σ uncertainty from Monte Carlo simulations using an uncertainty of ±0.1 based on the maximum range of inferred in our dataset () when calculated using the upper limit-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 – HMM 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) and providing open-source C code 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 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. 3d, Fig S1 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) Day 1 FI data, as reported to HVO. FI-derived depths are consistent with the estimated depths of the HMM reservoir. Kolmogorov-Smirnoff tests indicate that September 2023 FI are recording significantly shallower depths than 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 (LERZ) eruption, which required a contribution from the SC reservoir* (Wieser *et al.*, 2021; DeVitre and Wieser, 2024)*. 1LERZ 2018 melt inclusion data* (Wieser *et al.*, 2021)*; 2LERZ 2018 fluid inclusion data* (DeVitre and Wieser, 2024)*. c) Day 2 data, as reported, confirmed a likely dominant role for the Halemaʻumaʻu reservoir. A conservative degassing filter was applied (SO2/CO2 peak ratio < 0.1). d) Day 4 data, as reported. Means were taken for repeated analyses of single FI and more stringent data filters, FI-specific temperatures, and a more appropriate crustal density model (~2300 kg/m3 with a normal error distribution of 100 kg/m3) were applied. We also filtered using an SO2/CO2 peak ratio < 0.22. Error bars correspond to uncertainties propagated using Monte Carlo simulations and olivine Fo equilibrium field is calculated based on Glass EPMA data collected on September 11, 2023 (see Supplementary Information S1 Appendix). The shifted histogram ‘H2O effect’ shows the effect of H2O corrections on pressures recalculated using inferred from MI data (Wieser et al., 2021; DeVitre and Wieser, 2024).*

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 (N=16) 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 9 MI from the 2018 eruption with sufficient data to calculate saturation pressures (counting MI with glass major element contents and H2O contents, MI with glass CO2 measurements if there was no bubble, and glass + bubble measurements if a bubble was present). Using the same criteria, Aster *et al.*, (2016) only reported 13 MI complete measurements from Lassen Peak.

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 on Day 4 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 ~ 2 yrs. 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**

The 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 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 contents, and the effect on calculated pressures from fluid inclusions.

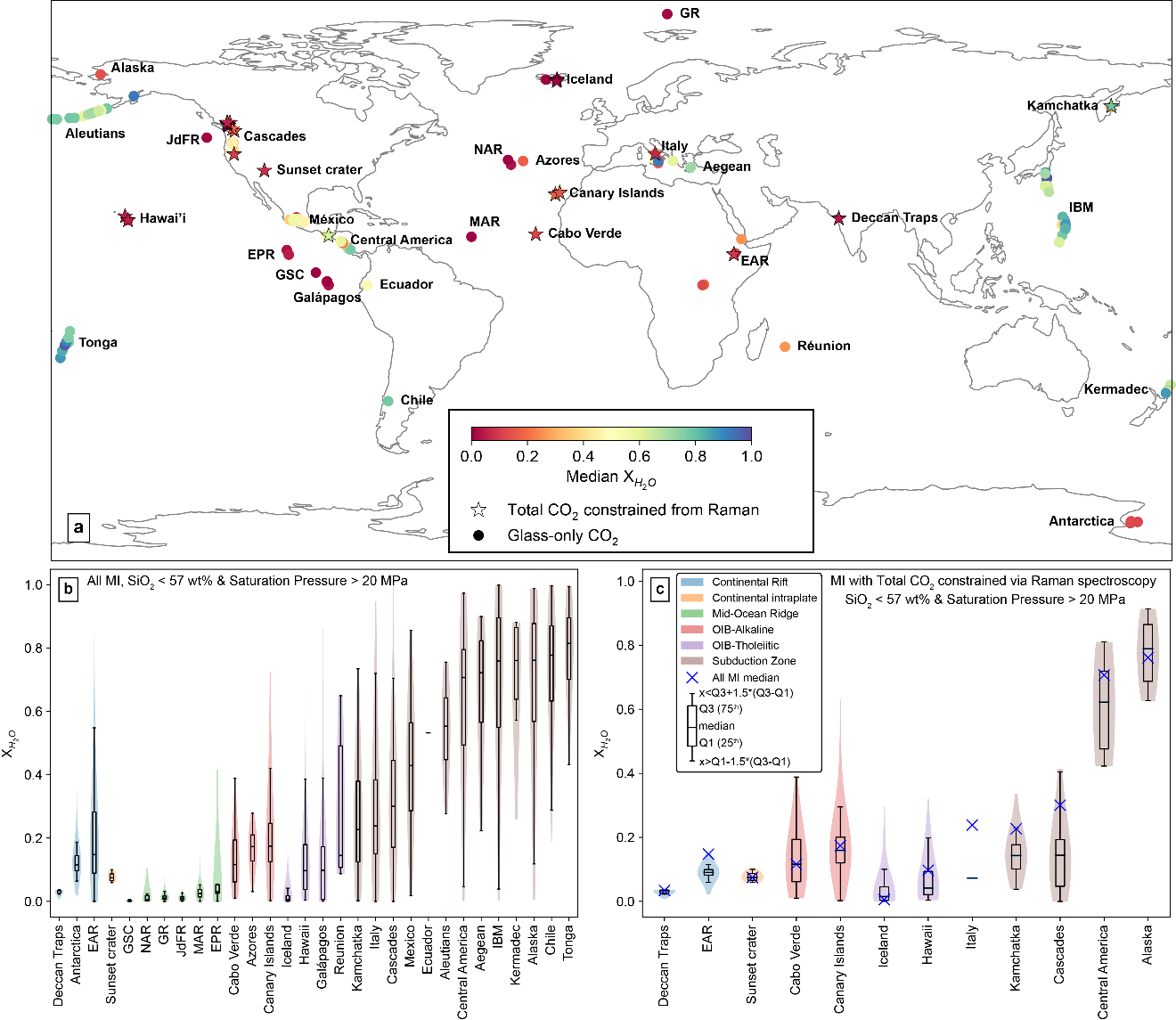
We compiled published melt inclusion data from all over the world, spanning many different tectonic settings (Fig. 4). We calculate using the solubility model MagmaSat (Ghiorso and Gualda, 2015), implemented in VESIcal (Iacovino *et al.*, 2021). We show the distribution, median, 25th and 75th quantiles of calculated for 4069 melt inclusions with SiO2 < 57 wt%, MgO < 16 wt% and Saturation Pressure > 20 MPa on Fig 4b-c, coloured by tectonic setting. For each volcano, there is a clear correlation between and pressure with 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 25th quantiles are likely most representative of in the main magma storage region. We stress the importance of considering when determining the suitability of this method to a particular system given that the pressure correction tends to be more significant at higher entrapment pressures. For example, if we consider an of 0.1 (the median of our FI dataset at Kīlauea and a commonly assumed 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 is greater than 0.1 (e.g., for =0.2, the correction is 25-30% at P<150 MPa and ~50% at P = 700 MPa; Fig 1). We plot on Fig 4a the median for magmas with SiO2 < 57 wt% and MgO < 16 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 overestimated. This can be demonstrated by comparing 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 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, Hawai’i, Galápagos, Réunion, Deccan Traps) generally have lower 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 Hawai’i, Iceland, East African Rift (EAR), Galápagos, Réunion, Cabo Verde, and the Canary Islands, it is not appropriate in subduction zones such as Alaska, Kamchatka, or Central America. Interestingly, although there are only two studies with Raman data in the Cascade arc (Aster *et al.*, 2016; Venugopal *et al.*, 2020), it is noteworthy that the highest pressure inclusions have 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 in more volcanic systems worldwide, given the large offsets between studies accounting bubbles and those which do not in for space (Fig. 4). Ideally, for maximum accuracy of fluid inclusions as a rapid response method, it should be a priority to determine approximate trends in -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 can provide a first order assessment of appropriate values to use. We note that once arc magmas are excluded from the compilation, even if is entirely unconstrained, fluid inclusion barometry is still more accurate than other methods such as mineral-melt thermobarometry.



*Figure 4. Global compilation of in the exsolved fluid phase from melt inclusion data for Continental Rift, Continental Intraplate, Alkaline and Tholeiitic Ocean Island Basalt (OIB, see Fig S7) Mid-Ocean Ridge and Subduction Zone volcanoes (details and references in the supplement). Data is filtered to SiO2 < 57 wt%, MgO < 16 wt% and Saturation Pressure >20 MPa (supplement for details). (a) World map coloured by Median 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 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 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, MAR – Mid-Atlantic Ridge, EPR – East Pacific Rise, IBM – Izu Bonin Mariana.*

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). Importantly, this simulation shows that rapid response work in collaboration with universities was not taxing on observatory staff, particularly considering the usefulness of information provided. This means this methodology can be employed during future eruptions to help observatories deduce the geometry of the plumbing system supplying magma, adding a crucial information for interpreting activity (Re *et al.*, 2021), without retracting from other essential duties during eruption responses. For example, during the 2018 Kilauea eruption, HVO’s near real time chemical monitoring with bulk rock ED-XRF identified the appearance and disappearance of many magma batches (Gansecki *et al.*, 2019), fluid inclusion barometry could have linked these distinct chemical signatures to different storage regions, addressing the questions of scientists and residents alike. Similarly, the return of eruptive activity at Kīlauea in 2020 after this event was accompanied by many questions about how the magmatic plumbing system had changed following the summit collapse in 2018 (Lynn et al., 2024). FI barometry would have been a critical addition to understanding the eruption and the system.

Our global compilation of values shows that Raman-based FI barometry has utility as a rapid-response petrological monitoring method at many of the world’s 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 drier arc magmas such as those found in the Cascades).

Overall, fluid inclusion barometry is a broadly applicable, and adds valuable quantitative storage depth information that provides a key advancement for volcano observatories that utilize near-real-time geochemical monitoring to better understand eruptions as they unfold (See overview–Re *et al.* (2021); Hawai‘i–Gansecki *et al.* (2019); La Palma–Pankhurst *et al.* (2022); Fuego–Liu *et al.* (2020); Italy–Corsaro and Miraglia (2022)).

**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, provided eruption context and edited the manuscript. KJL and DD prepared the glass mount and did the EMPA glass analyses.

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**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 fluid inclusion dataset (S2 Dataset), the global melt inclusions dataset (S3 Dataset), a compilation of microphotographs of the FI and crystals that were used for navigation during the simulation (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.

**References**

Anderson, K. R., Johanson, I. A., Patrick, M. R., Gu, M., Segall, P., Poland, M. P., Montgomery-Brown, E. K. & Miklius, A. (2019). Magma reservoir failure and the onset of caldera collapse at Kīlauea Volcano in 2018. *Science*. American Association for the Advancement of Science **366**, eaaz1822.

Anderson, K. R. & Poland, M. P. (2016). Bayesian estimation of magma supply, storage, and eruption rates using a multiphysical volcano model: Kīlauea Volcano, 2000–2012. *Earth and Planetary Science Letters* **447**, 161–171.

Andrews, B. J. *et al.* (2019). Rapid experimental determination of magmatic phase equilibria: coordinating a volcanic crisis response protocol. paper presented at the AGU Fall Meeting 2019. AGU.

Aster, E. M., Wallace, P. J., Moore, L. R., Watkins, J., Gazel, E. & Bodnar, R. J. (2016). Reconstructing CO2 concentrations in basaltic melt inclusions using Raman analysis of vapor bubbles. *Journal of Volcanology and Geothermal Research* **323**, 148–162.

Baker, S. & Amelung, F. (2012). Top-down inflation and deflation at the summit of Kīlauea Volcano, Hawai‘i observed with InSAR. *Journal of Geophysical Research: Solid Earth* **117**.

Cooper, K. M. *et al.* (2023). Coordinating science during an eruption: lessons from the 2020–2021 Kīlauea volcanic eruption. *Bulletin of Volcanology* **85**, 29.

Corsaro, R. A. & Miraglia, L. (2022). Near Real-Time Petrologic Monitoring on Volcanic Glass to Infer Magmatic Processes During the February–April 2021 Paroxysms of the South-East Crater, Etna. *Frontiers in Earth Science*. Frontiers **10**.

Dayton, K. *et al.* (2023). Deep magma storage during the 2021 La Palma eruption. *Science Advances*. American Association for the Advancement of Science **9**, eade7641.

DeVitre, C. L. *et al.* (2023). Oceanic intraplate explosive eruptions fed directly from the mantle. *Proceedings of the National Academy of Sciences*. Proceedings of the National Academy of Sciences **120**, e2302093120.

DeVitre, C. L., Allison, C. M. & Gazel, E. (2021). A high-precision CO2 densimeter for Raman spectroscopy using a Fluid Density Calibration Apparatus. *Chemical Geology* **584**, 120522.

DeVitre, C. L. & Wieser, P. (2023). Reliability of Raman analyses of CO2-rich fluid inclusions as a rapid barometer at Kīlauea. EarthArXiv.

DeVitre, C. L. & Wieser, P. E. (2024). Reliability of Raman analyses of CO2-rich fluid inclusions as a geobarometer at Kīlauea. *Geochemical Perspectives Letters* **29**, 1–8.

Dietterich, H. R. & Neal, C. A. (2022). A look ahead to the next decade at US volcano observatories. *Bulletin of Volcanology* **84**, 63.

Duan, Z. & Zhang, Z. (2006). Equation of state of the H2O, CO2, and H2O–CO2 systems up to 10 GPa and 2573.15K: Molecular dynamics simulations with ab initio potential surface. *Geochimica et Cosmochimica Acta* **70**, 2311–2324.

Esposito, R., Badescu, K., Boyce, J. W. & Frezzotti, M.-L. (2023). Chemical characterization of a magma recharging and mixing before an eruption: Insights from chronologically constrained melt inclusions. *Lithos* **456–457**, 107301.

Gansecki, C., Lee, R. L., Shea, T., Lundblad, S. P., Hon, K. & Parcheta, C. (2019). The tangled tale of Kīlauea’s 2018 eruption as told by geochemical monitoring. *Science*. American Association for the Advancement of Science **366**, eaaz0147.

Ghiorso, M. S. & Gualda, G. A. R. (2015). An H2O–CO2 mixed fluid saturation model compatible with rhyolite-MELTS. *Contributions to Mineralogy and Petrology* **169**, 53.

Helz, R. T., Clague, D. A., Sisson, T. W. & Thornber, C. R. (2014). *Petrologic insights into basaltic volcanism at historically active Hawaiian volcanoes*. *Characteristics of Hawaiian volcanoes*. US Geological Survey, Professional Papers, 237–294.

Iacovino, K., Matthews, S., Wieser, P. E., Moore, G. M. & Bégué, F. (2021). VESIcal Part I: An Open-Source Thermodynamic Model Engine for Mixed Volatile (H2O-CO2) Solubility in Silicate Melts. *Earth and Space Science* **8**, e2020EA001584.

Lerner, A. H. *et al.* (2021). The petrologic and degassing behavior of sulfur and other magmatic volatiles from the 2018 eruption of Kīlauea, Hawaiʻi: melt concentrations, magma storage depths, and magma recycling. *Bulletin of Volcanology*. Springer **83**, 1–32.

Lerner, A. H., Sublett, D. M., Wallace, P. J., Cauley, C. & Bodnar, R. J. (2024). Insights into magma storage depths and eruption controls at Kīlauea Volcano during explosive and effusive periods of the past 500 years based on melt and fluid inclusions. *Earth and Planetary Science Letters* **628**, 118579.

Liu, E. J., Cashman, K. V., Miller, E., Moore, H., Edmonds, M., Kunz, B. E., Jenner, F. & Chigna, G. (2020). Petrologic monitoring at Volcán de Fuego, Guatemala. *Journal of Volcanology and Geothermal Research* **405**, 107044.

Lynn, K. J., Nadeau, P. A., Ruth, D. C. S., Chang, J. C., Dotray, P. J. & Johanson, I. A. (2024). Olivine diffusion constrains months-scale magma transport within Kīlauea volcano’s summit reservoir system prior to the 2020 eruption. *Bulletin of Volcanology* **86**, 31.

Mourey, A. J., Shea, T., Costa, F., Shiro, B. & Longman, R. J. (2023). Years of magma intrusion primed Kīlauea Volcano (Hawai’i) for the 2018 eruption: evidence from olivine diffusion chronometry and monitoring data. *Bulletin of Volcanology* **85**, 18.

Pankhurst, M. J. *et al.* (2022). Rapid response petrology for the opening eruptive phase of the 2021 Cumbre Vieja eruption, La Palma, Canary Islands. *Volcanica* **5**, 1–10.

Pietruszka, A. J., Heaton, D. E., Marske, J. P. & Garcia, M. O. (2015). Two magma bodies beneath the summit of Kīlauea Volcano unveiled by isotopically distinct melt deliveries from the mantle. *Earth and Planetary Science Letters* **413**, 90–100.

Pietruszka, A. J., Marske, J. P., Heaton, D. E., Garcia, M. O. & Rhodes, J. M. (2018). An Isotopic Perspective into the Magmatic Evolution and Architecture of the Rift Zones of Kīlauea Volcano. *Journal of Petrology* **59**, 2311–2352.

Pritchard, M. E., Mather, T. A., McNutt, S. R., Delgado, F. J. & Reath, K. (2019). Thoughts on the criteria to determine the origin of volcanic unrest as magmatic or non-magmatic. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. Royal Society **377**, 20180008.

Re, G., Corsaro, R. A., D’Oriano, C. & Pompilio, M. (2021). Petrological monitoring of active volcanoes: A review of existing procedures to achieve best practices and operative protocols during eruptions. *Journal of Volcanology and Geothermal Research* **419**, 107365.

Ryan, M. P. (1987). The elasticity and contractancy of Hawaiian olivine tholeiite, and its role in the stability and structural evolution of sub-caldera magma reservoirs and rift systems. In Volcanism in Hawaii. *US Geol. Surv. Prof. Pap.* **1350**, 1395–1447.

Span, R. & Wagner, W. (1996). A new equation of state for carbon dioxide covering the fluid region from the triple‐point temperature to 1100 K at pressures up to 800 MPa. *Journal of physical and chemical reference data*. American Institute of Physics for the National Institute of Standards and … **25**, 1509–1596.

Venugopal, S., Moune, S., Williams-Jones, G., Druitt, T., Vigouroux, N., Wilson, A. & Russell, J. K. (2020). Two distinct mantle sources beneath the Garibaldi Volcanic Belt: Insight from olivine-hosted melt inclusions. *Chemical Geology* **532**, 119346.

Welsch, B., Faure, F., Famin, V., Baronnet, A. & Bachèlery, P. (2013). Dendritic Crystallization: A Single Process for all the Textures of Olivine in Basalts? *Journal of Petrology* **54**, 539–574.

Wieser, P. E. *et al.* (2021). Reconstructing Magma Storage Depths for the 2018 Kı̄lauean Eruption From Melt Inclusion CO2 Contents: The Importance of Vapor Bubbles. *Geochemistry, Geophysics, Geosystems* **22**, e2020GC009364.

Wieser, P. E., Edmonds, M., Maclennan, J., Jenner, F. E. & Kunz, B. E. (2019). Crystal scavenging from mush piles recorded by melt inclusions. *Nature Communications*. Nature Publishing Group **10**, 5797.

Wieser, P. E., Kent, A. J. R. & Till, C. B. (2023a). Barometers Behaving Badly II: a Critical Evaluation of Cpx-Only and Cpx-Liq Thermobarometry in Variably-Hydrous Arc Magmas. *Journal of Petrology* **64**, egad050.

Wieser, P. E., Kent, A., Till, C. & Abers, G. (2023b). Geophysical and Geochemical Constraints on Magma Storage Depths along the Cascade Arc: Knowns and Unknowns. EarthArXiv.

Yoshimura, S. (2023). Carbon dioxide and water in the crust. Part 1: Equation of state for the fluid. *Journal of Mineralogical and Petrological Sciences* **118**, 221224a.

Zanon, V., D’Auria, L., Schiavi, F., Cyrzan, K. & Pankhurst, M. J. (2024). Toward a near real-time magma ascent monitoring by combined fluid inclusion barometry and ongoing seismicity. *Science Advances*. American Association for the Advancement of Science **10**, eadi4300.