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

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

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ABSTRACT

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. The depth of magma storage has recently been identified as high-priority information for volcanic observatories that is not currently obtainable on timescales relevant to eruption response. To address this deficiency, we performed a rapid-response simulation for the September 2023 eruption of Kīlauea. We show that Raman-based fluid~~-~~ inclusion barometry can robustly determine reservoir depths within a day of receiving samples - a transformative timescale for ~~decision making~~decision-making that has not previously been achieved by petrological methods. Additionally, our global melt~~-~~ inclusion compilation for which we calculated fluid composition at the point of vapour saturation demonstrates the robustness of the fluid~~-~~ inclusion method at many of the world's most active and hazardous mafic 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

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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 (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 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 this, it is imprecise (Wieser *et al.*, 2023a), and therefore can only constrain magma storage to very broad regions (e.g., crust vs. sub-Moho). It 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

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which is not ~~pressure~~ pressure-sensitive, and where a precision of 1–2 km is needed to distinguish between reservoirs (Baker and Amelung, 2012; Anderson and Poland, 2016).

Recent developments have shown that Raman-based barometry of CO_2-rich fluid~~-~~ inclusions provides an alternative, with much smaller uncertainties than mineral barometry, and requiring far less time and resources than melt~~-~~ inclusion analyses (Dayton *et al.*, 2023; DeVitre and Wieser, 2024). This method uses spectral features of CO_2 fluids to calculate a CO_2 density using an ~~instrument~~ instrument-specific calibration (DeVitre *et al.*, 2021). Along with an estimate of entrapment temperature, this density is converted into an entrapment pressure using a CO_2 Equation of State (EOS, Fig. 1). One major advantage is that the conversion of CO_2 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). The difference in pressure for EOS calculations considering 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~~)~~) is at most ~20~~–~~%, which corresponds to ~0.2-0.4 km at depths representative of the Halema‘uma‘u reservoir (1-2 km), and ~0.6-1.0 km at the depths of the South~~-~~ Caldera reservoir (3-5 km; Fig. 1b and Fig. S3-S6). 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).

Recent studies have speculated that fluid~~-~~ inclusion barometry could be performed quickly enough to be useful for ~~near~~ near-real-time volcano monitoring (Dayton *et al.*, 2023; Zanon *et al.*, 2024). Here, we performed a ~~near~~ near-real-time simulation to rigorously assess how quickly fluid~~-~~ inclusion depths can be obtained from erupted

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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~~ low-hazard eruptions (as here) or as hypothetical simulations (e.g., ~~(~~Andrews *et al.*, 2019~~)~~) is vital to iron~~-~~ out bottlenecks 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 can feasibly be employed during future eruptions.

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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 (Halema‘uma‘u at 1-2 km and South~~-~~ Caldera at 3-5 km) at this volcano have been well constrained by various independent geophysical and petrological methods, including prior fluid~~-~~ inclusion 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 15~~th~~ (Fig. S1). A schematic of the workflow and detailed timeline is available in the supplement (Fig. S1).

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Our simulation started on September 20 at 9 am PST (Day 1), the morning after sample receipt (Fig. S1). We used a production~~- line~~ 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, fluid~~-~~ inclusion preparation, sample cataloguing, and analysis. We crushed and sieved tephra, picked olivine crystals (size fractions 0.5-1 and 1-2 mm), and mounted them in CrystalBond™* to search for fluid~~-~~ inclusions. By ~2 pm PST, we collected our first Raman spectra, and by ~7 pm PST, we had calculated CO_2~~-~~ densities from 16 fluid~~-~~ inclusions using a previously established instrument-specific calibration of the relationship between CO_2 density and Fermi diad splitting distance (DeVitre *et al.*, 2021; DeVitre and Wieser, 2024). We calculated pressures using the pure CO_2 EOS of Span & Wagner (1996). At the time of our simulation, it was challenging to perform EOS calculations considering the possible presence of H_2O in the exsolved fluid due to a lack of publicly available software running on modern operating systems. However, recent work by Yoshimura (2023) identified errors in the published equations for the H_2O-CO_2 EOS of Duan & Zhang (2006) and provided open-source C code meaning that such calculations can be now be performed in DiadFit. Using estimates of X_{H_2O} 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~~—~~ CO_2-H_2O EOS had been used (Fig. 2d, Fig S1 in supplementary materials). This does not affect the interpretation of our results, as the shift is far smaller than the pressure offset between the Halema‘uma‘u and South~~-~~ Caldera reservoir.

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For the first and second days of the simulation, we assumed an entrapment temperature of 1150 ˚C for all fluid~~-~~ inclusions, based on geothermometric estimates of previously erupted liquids (Gansecki *et al.*, 2019; DeVitre and Wieser, 2024). On ~~day~~ Day 4, we calculated entrapment temperatures for each fluid~~-~~ inclusion~~–~~ using the host forsterite content measured by EDS (DeVitre and Wieser, 2024), yielding temperatures spanning 1182–1307 ˚C. 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. 2a-b) of storage depths with HVO collaborators showing that crystals, and thus magma, were likely coming from the shallower Halemaʻumaʻu reservoir of Kīlauea (Fig. 2a-b). It worthwhile to note that the number of fluid~~-~~ inclusions reported on Day 1 (N=16) is comparable to many melt~~-~~ inclusion (MI) studies, which often aim for ~20 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 H_2O contents, MI with glass CO_2 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 complete measurements from Lassen Peak.

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We also had an additional ~20 fluid inclusions fully prepared and catalogued for analysis by the end of Day 1. On Day 2, these 20 fluid inclusions were analysed, while additional fluid inclusions were prepared and catalogued. After analysis of ~15 samples, the crystals were removed from CrystalBond™* and placed on tape for epoxy mount-making. Epoxy was poured at the end of Day 2. By ~8:30 pm PST on Day 2, we shared an updated histogram of 46 fluid inclusion pressures and depths from 28 crystals, confirming the dominant contribution of the Halemaʻumaʻu reservoir (Fig. 2a and c). On Day 3, we finished analysing the remaining prepared fluid inclusions. Then we polished the epoxy mount and catalogued the regions of crystals closest to each fluid inclusion 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. 2d). The Fo content of an olivine is a function of MgO and FeO in the liquid and the Ol-Liq partitioning coefficient (K_D). Thus, the Fo contents of the host olivine close to each fluid inclusion 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 (DeVitre and Wieser, 2024) for performing EOS calculations, rather than having to use a uniform temperature as on Day 1-2. We thus recalculated all fluid inclusion pressures on Day 4 using fluid ~~inclusion~~ inclusion-specific entrapment temperatures.

Our results on Day 4 clearly show that the majority of fluid inclusions were entrapped at ~1–2 km below the surface (Fig. 2d), which aligns well with the depths of the Halemaʻumaʻu reservoir interpreted from geophysics (Baker and Amelung, 2012; Anderson and Poland, 2016;

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Anderson *et al.*, 2019), melt~~-~~ inclusion barometry (Lerner *et al.*, 2021; Wieser *et al.*, 2021), and fluid~~-~~ inclusions (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 fluid~~-~~ inclusion reveal that olivine crystals grew from a wide range of melt compositions. It is interesting to note that fluid~~-~~ inclusions in the cores of high-Fo (e.g., >86) olivine crystals return pressures indicative of the shallower Halema‘uma‘u 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 (Fig. 2a) where ~~high~~ 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) Fluid~~-~~ inclusions in high-Fo olivine crystals were entrapped within the South~~-~~ Caldera reservoir and then transported into the Halema‘uma‘u reservoir, where the fluid~~-~~ inclusions 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 Halema‘uma‘u reservoir, where high-Fo olivine crystallized and trapped fluid~~-~~ inclusions at shallow depths (Lerner *et al.*, 2024).

3) Complex skeletal growth of olivine crystals during extensive undercooling (Welsch *et al.*, 2013) could mean that high-Fo olivine cores which initially grew in the South~~-~~ Caldera reservoir texturally evolved and trapped lower pressure fluid~~-~~ inclusions in the Halema‘uma‘u reservoir.

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We think that scenario 1 is unlikely given the that fluid~~-~~ inclusions from the 2018 LERZ eruption appear not to have re-equilibrated despite stalling in the Halema‘uma‘u reservoir for up to 2 years (Mourey *et al.*, 2023; DeVitre and Wieser, 2024), and our models of fluid~~-~~ inclusion re-equilibration indicate <10% change in pressure over ~ 2 yrs. Current data do~~es~~ 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~~ phosphorus mapping in olivine around fluid~~-~~ inclusions (e.g., melt~~-~~ inclusions in Esposito *et al.*, 2023). Regardless of the exact mechanism, our fluid~~-~~ inclusion pressures indicate that the erupted crystal cargo experienced storage at Halema‘uma‘u reservoir depths prior to eruption, and thus this was the most probable reservoir supplying magma to the surface in the September 2023 eruption.

BROADER APPLICABILITY OF THE METHOD

The use of a pure CO_2 EOS results in an underestimate of the entrapment pressure of fluid~~-~~ inclusions if there was H_2O in the fluid at the time of inclusion entrapment (Fig. 2). At Kīlauea, melt~~-~~ inclusion data indicates that the exsolved fluid phase is ~90% CO_2 at pressures corresponding to the Halema’uma’u reservoir, and >95% CO_2 at pressures indicative of the South~~-~~ Caldera reservoir (Wieser *et al.*, 2021; DeVitre and Wieser, 2024). As discussed above, the effect of X_{H_2O} is small on calculated pressures presented here (Fig. 2d). However, to assess the utility of the fluid~~-~~ inclusion method for rapid-response petrology globally, it is necessary to evaluate X_{H_2O} contents, and their effect on fluid~~-~~inclusion pressures.

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We compiled published melt~~-~~ inclusion data from all over the world, spanning many different tectonic settings (Fig. 3). We calculate X_{H_2O} 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 X_{H_2O} for 4069 melt~~-~~inclusions with SiO_2 < 57 wt%, MgO < 16 wt% and ~~Saturation~~ saturation ~~Pressure~~ pressure > 20 MPa on Fig 3b-c, coloured by tectonic setting. For each volcano, there is a clear correlation between X_{H_2O} and pressure~~,~~ where X_{H_2O} becomes very high at shallow pressures (Fig. S9a-i) as melt~~-~~ inclusions are trapped during enhanced degassing of H_2O upon ascent. Thus, in this compilation, the median and 25th quantiles are likely most representative of X_{H_2O} in the main magma storage region. We stress the importance of considering X_{H_2O} when determining the suitability of this method to a particular system given that the X_{H_2O} pressure correction tends to be more significant at higher entrapment pressures. For example, if we consider an X_{H_2O} of 0.1 (the median X_{H_2O} of our fluid~~-~~inclusion dataset at Kīlauea and a commonly assumed X_{H_2O} 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 X_{H_2O} is greater than 0.1 (e.g., for X_{H_2O}=0.2, the correction is 25-30% at P<150 MPa and ~50% at P = 700 MPa; Fig 1).

~~Noteworthy~~Notably, most melt~~-~~ inclusion suites in ~~this~~ our global compilation did not measure CO_2 in the vapour bubble, meaning that the total CO_2 content has been underestimated, and X_{H_2O} overestimated. This can be demonstrated by comparing X_{H_2O} values at volcanoes where there are some studies with Raman measurements and some

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without (Fig. S9c EAR; Fig. S9h Kamchatka, and Cascades).~~—~~ Thus, Fig. 3c shows a compilation only using melt~~-~~ inclusions where bubble CO_2 was measured by Raman spectroscopy.

Both compilations demonstrate that subduction zones record much higher X_{H_2O} globally than ~~Mid~~mid-~~Ocean~~ ocean ~~Ridge~~ 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 X_{H_2O} 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).

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Thus, while rapid-response fluid~~-~~ inclusion barometry is highly applicable to active volcanic regions such as Hawai'i, Iceland, East African Rift, 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 Cascades arc (Aster *et al.*, 2016; Venugopal *et al.*, 2020), the inclusions with highest pressures have X_{H_2O} values <0.2. This may indicate that in ~~dryer~~ drier subduction zones, fluid~~-~~ inclusions may have some utility for the most mafic, CO_2-rich magmas.

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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 CO_2 in more volcanic systems worldwide, given the large offsets between studies

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accounting for bubbles and those which do not in ~~for~~ X_{H_2O} space (Fig. 3), and to determine approximate trends in X_{H_2O}-pressure space for a given volcanic system or region during times of quiescence. This will allow assessment of the suitability of the fluid~~-~~ inclusion method for a given volcano, 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 X_{H_2O} can provide a ~~first~~ first-order assessment of appropriate X_{H_2O} values to use. We note that once arc magmas are excluded from the compilation, even if X_{H_2O} is entirely unconstrained, fluid~~-~~ inclusion barometry is still more accurate than other methods such as mineral-melt thermobarometry in recovering magma storage pressures.

CONCLUSION

~~This~~ Our 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~~ measure olivine Fo contents has been around for 15 years (S1 Appendix). Importantly, this simulation ~~shows~~ showed that rapid-response work in collaboration with universities was not taxing on observatory staff, particularly considering the usefulness of information

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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~~ detracting from other essential duties during eruption responses. For example, during the 2018 LERZ Kilauea eruption, HVO's ~~near~~ near-~~real~~ real-time chemical monitoring with bulk rock ED-XRF identified the appearance and disappearance of many magma batches (Gansecki *et al.*, 2019)~~,~~. F~~f~~luid~~-~~ 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 was accompanied by many questions about how the magmatic plumbing system had changed following the summit collapse in 2018 (Lynn *et al.*, 2024). Fluid~~-~~ inclusion barometry would have been a critical addition to understanding the eruption and the system.

Our global compilation of X_{H_2O} values shows that Raman-based fluid~~-~~ inclusion 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 CO_2 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 in the Cascades).

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Overall, fluid~~-~~ inclusion barometry is 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~~ see overview–(Re *et al.*, 2021); Hawai'i–(Gansecki *et al.*,

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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. S1. CD and PW wrote the paper. CD, PW, AR, BR, and AB prepared tephra, picked olivine, found fluid~~-~~ inclusions, 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. S1 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~~ EPMA 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 fluid~~-~~ inclusions and crystals that were used for navigation only 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 at the following link: https://github.com/cljdevitre/2023_Kilauea-rapid-response-simulation. The Github repository will be archived on Zenodo upon acceptance.

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FIGURE CAPTIONS

Figure 1*. *Sensitivity of fluid~~-~~ inclusion barometry to temperature and molar proportions of H_2O in the exsolved fluid phase (X_{H_2O}). *(a) CO_2 density vs ~~Pressure~~ 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 days 1 and 2 of the simulation, 1240 ˚C is the rounded mean and median of all measured temperatures in our final dataset. (b) Panel a close-up. Grey boxes show Kīlauea magma storage inferred from fluid~~-~~ inclusions, melt~~-~~ inclusions and geophysics* (DeVitre and Wieser, 2024; Lerner *et al.*, 2024). *HMM= Halema'uma'u reservoir, SC = South~~-~~ Caldera reservoir. Stars show hypothetical fluid~~-~~ inclusions trapped at Halema'uma'u and South~~-~~ Caldera with T=1150 ˚C and error~~-~~ bars represent~~ing~~ 1σ uncertainty from Monte Carlo simulations using a temperature uncertainty of ±125 ˚C ($\frac{1350°C - 1100°C}{2}$). (c) CO_2 density vs ~~Pressure~~ pressure at 1150 ˚C for various X_{H_2O} using the mixed H_2O-CO_2 EOS of* Duan and Zhang (2006). *The small discontinuity at 200 MPa is due to parameter values being switched* (Yoshimura, 2023). *(d) Panel c close-up. Stars show hypothetical fluid~~-~~ inclusions trapped at Halema'uma'u and South~~-~~ Caldera with T~~-~~=~~-~~1150 ˚C, X_{H_2O} inferred using the X_{H_2O} -P relationship of* DeVitre and Wieser (2024)~~.~~ *and error~~-~~ bars represent~~ing~~ 1σ uncertainty from Monte Carlo simulations using an X_{H_2O} uncertainty of ±0.1 based on the maximum range of X_{H_2O} inferred in our dataset ($\frac{XH_2Omax - XH_2Omin}{2}$) when calculated using the upper limit X_{H_2O}-P relationship for Kīlauea from DeVitre and Wieser (2024).*

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Commented [MH14]: As an aside, as a Windows user I wasn't able to open the .eps files, and the pdf reproductions supplied by the journal are often not very high resolution. It's helpful if figures can be supplied in pdf format.

Commented [MH15]: To compare the two different equations of state it would help for panels (a) and (c) to have the same scale on the x and y axes. Is the pressure-depth conversion done differently in (a) and (c) or is this an artefact of how the axes are labelled?

Figure 2. Evolution of results over 4 days. *a) Schematic model of Kīlauea's plumbing system, indicating reservoir depths (HMM = Halema'uma'u; SC = South~~-~~ Caldera). b) Day 1 fluid~~-~~ inclusion depths, as reported to HVO, are consistent with the estimated depths of the Halema'uma'u reservoir. Kolmogorov-Smirnoff tests indicate that September 2023 fluid~~-~~ inclusions record significantly shallower depths than fluid~~-~~ inclusions (critical D = 0.22, stat = 0.24, pval=0.016) and melt~~-~~ inclusions (critical D = 0.22, stat = 0.41, pval=3.51e-06) from the 2018 ~~lower~~ Lower East Rift Zone (LERZ) eruption, which required a contribution from the South~~-~~ Caldera reservoir* (Wieser *et al.*, 2021; DeVitre and Wieser, 2024). [1]*LERZ 2018 melt~~-~~ inclusions* (Wieser *et al.*, 2021); [2]*LERZ 2018 fluid~~-~~ inclusions* (DeVitre and Wieser, 2024). *c) Day 2 data, as reported, confirmed a likely dominant role for the Halema'uma'u reservoir. A conservative degassing filter was applied (SO_2/CO_2 peak ratio <~~-~~0.1). d) Day 4 data, as reported. Means were taken for repeated analyses of single fluid~~-~~ inclusions and additional data filters (e.g., SO_2/CO_2 peak ratio <~~-~~0.22), fluid~~-~~ inclusion-specific temperatures, and a more appropriate crustal density model (~2300 kg/m^3 with a normal error distribution of 100 kg/m^3) were applied. Error~~-~~ bars correspond to uncertainties propagated using Monte Carlo simulations and olivine Fo equilibrium field is calculated based on ~~Glass~~ glass EPMA data collected on September 11, 2023 (see Supplementary Information S1 Appendix). The shifted histogram 'H$_2$O effect' shows the effect of H_2O corrections on pressures recalculated using X_{H_2O} inferred from melt~~-~~ inclusions* (Wieser *et al.*, 2021; DeVitre and Wieser, 2024).

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Figure 3. ***Global compilation of X_{H_2O} in the exsolved fluid phase from melt~~-~~inclusion data for ~~C~~continental ~~R~~rift, ~~C~~continental ~~I~~intraplate, ~~A~~alkaline and ~~T~~tholeiitic ~~O~~ocean ~~I~~island ~~B~~basalt (OIB, see Fig S7), ~~M~~mid-~~O~~ocean ~~R~~ridge and ~~S~~subduction ~~Z~~zone volcanoes (details and references in the supplement). Data ~~is~~ are filtered to SiO_2 <~~-~~57 wt%, MgO <~~-~~16 wt% and ~~S~~saturation ~~P~~pressure >20 MPa (supplement for details).*** *(a) World map coloured by ~~Median~~ median X_{H_2O} of the melt~~-~~ inclusion suites. C~~, c~~ircles indicate ~~G~~glass-only MI data and stars those for which CO_2 has been constrained by Raman. (b) Boxplot of X_{H_2O} 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 X_{H_2O} showing only MI suites which constrained ~~Total~~ total CO_2 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.*

> **Commented [MH16]:** I would suggest using first and third quartile, or 25th and 75th percentile.

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