Geophysical and Geochemical Constraints on Magma Storage Depths along the Cascade Arc: Knowns and Unknowns

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We have submitted to G3 (geochemistry, geophysics, geosystems).

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Key Points (140 characters or less)

1. The availability of magma storage depth constraints along the Cascade arc is highly variable and not well correlated to volcano threat level.

2. Available geophysical and geochemical constraints cluster at 0–15 km depth (~2±2 kbar), consistent with global compilations.

3. Investigating the potential for deeper storage of the most mafic magmas will require studies accounting for melt inclusion vapour bubble CO_2.

Abstract (can only be 250 words)

The iconic volcanoes of the Cascade arc stretch from Lassen Volcanic Center in northern California, through Oregon and Washington, to the Garibaldi Volcanic Belt in British Columbia. Recent studies have reviewed differences in the distribution and eruptive volumes of vents, as well as variations in geochemical compositions and heat flux along strike (amongst other characteristics). We investigate whether these along-arc trends manifest as variations in magma storage conditions. We compile available constraints on magma storage depths from InSAR, geodetics, seismic inversions, and magnotellurics for each major edifice, and compare these to melt inclusion saturation pressures, pressures calculated using mineral-only barometers, and constraints from experimental petrology. The availability of magma storage depth estimates varies greatly along the arc, with abundant geochemical and geophysical data available for some systems (e.g. Lassen Volcanic Center, Mount St. Helens), and very limited data available for other volcanoes, including many which are classified as “very high threat” by the USGS (e.g., Glacier Peak, Mount Baker, Mount Hood, Three Sisters). Acknowledging the limitations of data availability and the large uncertainties associated with certain methods, available data is indicative of magma storage within the upper 15 km of the crust (~2 ± 2 kbar) beneath the main edifices. These findings are consistent with previous work recognising barometric estimates cluster within the upper crust in many arcs worldwide. There are no clear offsets in magma storage between arc segments that are in extension, transtension or compression, although substantially more petrological work is needed for fine scale evaluation of storage pressures.

Plain language summary

The Cascade arc contains a number of large volcanoes which present a significant hazard to human populations and infrastructure (e.g., Mount St. Helens, Mount Rainier). Until now, there has been no wide-scale review of where magma (molten rock) is stored in the crust beneath these volcanoes, even though understanding where magma is stored is very important to help monitor unrest at these volcanoes and to predict future activity. We compile all available data on magma storage for each volcano, and find that there are many volcanoes have had very few studies investigating them, despite the risk they pose to society. The available data (albeit sparse) suggests that most magma is stored at 0–15 km depth before eruption.

Introduction

Determining the depths at which magmas are stored in continental arcs is a key parameter to help inform models of the formation and evolution of the continental crust (e.g., Ducea et al., 2015; Lee and Anderson, 2015; Rudnick, 1995), as well as to aid our understanding of volcanic eruptions and hazards. For example, precise determinations of magma storage depths help to distinguish between end-member models, where magmas may be distributed in a mush zone spanning the entire crust (Cashman et al., 2017), or concentrated in distinct magma storage reservoirs, such as Kilauea Volcano, (Poland et al., 2014; Wieser et al., 2021) and Benzmianny Volcano (Turner et al., 2013). Magma storage depths also influence the eruptive style, size and frequency of volcanic eruptions (Huber et al., 2019), and can be used to help interpret signals of volcanic unrest in monitoring data (Pritchard et al., 2019). Integration of petrological and geophysical constraints on magma storage depths was also identified as vital to improve our understanding of magma storage, staging and transport by the Subduction Zones in 4D (SZ4D) initiative (Hilley et al., 2022).

The Cascade arc presents an interesting case study to investigate magma storage depths, because of the wide variability in volcano morphology, magma compositions, and parameters relating to magma production along the arc (Hildreth, 2007; Till et al., 2019). The Cascade arc trends North-South along the Western margin of the US and Canada, forming as the result of the eastward subduction of the Juan de Fuca and Gorda plates beneath the North American plate. Quaternary activity in the Cascades has occurred at >2300 individual vents, with at least 30 topographically prominent edifices representing longer-lived magmatic systems (Hildreth, 2007). These larger edifices stretch from Lassen Peak in North California (USA) to Mount Meager in British Columbia (Canada) along an approximately linear trend, erupting mostly intermediate and silicic magmas (Fig. 1). The more distributed off-axis fields of smaller, often monogenetic vents are characterized by more mafic compositions (O'Hara et al., 2020). In addition to activity focused around the arc axis, there are also three prominent rear-arc volcanoes/volcanic fields (Simcoe Mountains, Newberry Volcano, and Medicine Lake; Donnelly-Nolan et al., 2008; Hildreth and Fierstein, 2015; Sherrod et al., 1997). This off axis volcanism is thought to be associated with the impingement of the Basin and Range extensional province on the eastern limit of Cascade volcanism (Guffanti and Weaver, 1988; Priest et al., 2013).

Volcanism in the Cascades presents a significant societal hazard. Fourteen Cascade edifices have been active since the late Holocene. 11 are classified by the USGS National Volcanic Threat assessment as “Very High Threat” (Mount St. Helens, Mount Rainier, Mount Shasta, Mount Hood, Three Sisters, Lassen Volcanic Center, Newberry Volcano, Mount Baker, Glacier Peak, Crater Lake; Ewert et al., 2018), while Mount Adams and Medicine Lake are listed as “High Threat” (Fig. 1).

Over the last few decades, a number of studies have reviewed various aspects of Cascade volcanism on an arc-scale. Hildreth (2007) provided a comprehensive summary of the number, location, and distribution of Quaternary vents, along with descriptions of eruptive activity and approximate volume estimates of different vents along the arc. Poland et al. (2017) reviewed geodetic data collected over several decades in the Cascades to investigate the diverse causes of surface deformation. From a geochemical perspective, Schmidt et al. (2008) and Pitcher and Kent (2019) reviewed the major, trace and isotopic composition of samples to assess compositional variability along the arc. Integrating geophysics and geochemistry, Till et al. (2019) examined variations in erupted volumes and compositions, heat budget, and seismic velocities along the Cascade arc to investigate the influence of crustal processes (e.g., tectonic stress state) vs. mantle processes (e.g., magma generation, variations in subduction parameters, mantle wedge dynamics) on Cascade variability.

While geophysical and petrological studies have been performed at individual centres to investigate the pressures, temperatures and timescales associated with the magmatic plumbing system, there has been no detailed arc-scale review of magma storage conditions. A brief compilation was presented by Dufek et al. (2022, their Fig. 3). However, data sources and uncertainty associated with each estimate were not discussed, and we have identified many additional constraints, both from the literature and our own petrological calculations. Based on the correlation between low seismic phase velocities and crustal heat flow, Till et al. (2019) suggest that crustal seismic structure and heat flow are primarily controlled by magmatic processes and advection of heat occurring in the upper mantle/deepest crust, and that the flux of mantle-derived basalt varies by a factor of two along strike in the Quaternary

Cascades. In ocean-island basalts, it has been shown that volcanoes with longer repose periods (a proxy for magma supply rate) are characterized by deeper magma storage (Gleeson et al., 2021). This correlation may indicate that large melts fluxes are required to maintain active crustal storage reservoirs in the cooler upper crust. Thus, it may be expected that shallower magma storage depths are found in regions of the arc with higher mantle supply. Alternatively, magma storage in the Cascades may be controlled by crustal processes such as the crustal stress state, prominent lithological or density boundaries within the crust (Chaussard and Amelung, 2014), or magmatic H_2O contents (Rasmussen et al., 2022).

Numerous methods have been used to determine magma storage depths in the Cascades and elsewhere. These can broadly be subdivided into geophysical and petrological methods. One common petrological method is thermobarometry, which relies on pressure-sensitivity of the exchange of chemical components within a single mineral, between two minerals, or between minerals and the liquid from which they crystallize or re-equilibrate with (see Putirka, 2008). In the Cascades, equilibrium between clinopyroxene and liquid (Cpx-Liq), clinopyroxene-orthopyroxene (Cpx-Opx), and amphibole-liquid (Amp-Liq), as well as liquid compositions themselves have been used to determine magma storage conditions (e.g., Blundy, 2022; Hollyday et al., 2020; Scruggs and Putirka, 2018). Melt inclusion barometry is another petrological technique that has been applied to the Cascades (e.g., Aster et al., 2016; Ruscitto et al., 2010; Wright et al., 2012), which relies on the strong relationship between pressure and the concentration of CO_2 and H_2O in a volatile-saturated silicate melt (e.g., Dixon, 1997; Ghiorso and Gualda, 2015; Shishkina et al., 2014). After measuring the volatile (and major element) contents of melt inclusions (MIs) at the time at which these pockets of melt were trapped within crystals, a mixed fluid solubility model can be used to calculate the minimum pressure at which the magma was volatile saturated. Finally, experimental petrology can be used to determine the conditions of magma storage, by comparing the chemistry of erupted products to experiments conducted at varying pressure, temperature, fluid compositions (e.g., Mandler et al., 2014; Quinn, 2014).

Various geophysical methods for imaging magma bodies have been applied to the Cascades. Magnetotellurics is used to image the conductivity structure of the crust, which can help identify regions of melt and fluid, as well as hot intrusions (e.g., Bedrosian et al., 2018; Bowles-Martinez and Schultz, 2020). Seismic tomography using natural earthquakes or controlled sources (e.g., Kiser et al., 2016; Moran et al., 1999; Ulberg et al., 2020; Zucca and Evans, 1992) and methods that use the ambient seismic noise wavefield (e.g., Flinders and Shen, 2017; Heath et al., 2018; Jiang et al., 2023) have been used to probe the elastic velocity structure of the crust. Seismic wave velocities are sensitive to composition and mineralogy, temperature, and the presence of melt or other fluids, while the attenuation of seismic waves is relatively more sensitive to temperature and fluids (Abers and Hacker, 2016; Magee et al., 2018).

A variety of geodetic methods (e.g., tilt, levelling, GPS and InSAR; Dzurisin et al., 2009; Mastin et al., 2008; Poland et al., 2017) can be used to identify changes in the ground surface around volcanoes, which can help identify intrusion of new magma into the crust. Seismicity also provides an indicator of deformation associated with magma movement, delineating pathways of magma transport (e.g., Jones and Malone, 2005). However, as for petrological methods, many caveats exist for these geophysical methods. For example, ground deformation and earthquakes can arise from both volcanic and tectonic processes (Dzurisin et al., 2006; Jones and Malone, 2005; Poland et al., 2006), and it can be difficult to robustly distinguish crustal velocity and conductivity anomalies from magma, hot but solidified intrusions, and other compositional variations such as sedimentary units (e.g., Bedrosian et al., 2018 vs. Flinders and Shen, 2017; Bowles-Martinez and Schultz, 2020).

Here, we compile available geophysical and geochemical magma storage depths for the main Cascade volcanic centres (Fig. 1). We anticipate that this review will serve several purposes. Firstly, it can be used as a reference of available storage depths at each volcano. Perhaps more importantly, it is very helpful to identify high threat volcanoes where data is very sparse, and future work should be prioritized.

Methods

When compiling and collating magma storage depths along the arc into a single coherent database, it is important to ensure consistency between published depth estimates from different volcanoes. We discuss the approaches used below for each proxy to ensure consistency along-arc.

Mineral barometry

For mineral-melt barometry, we compile Amp and Cpx compositions from a wide variety of studies, along with a smaller number of matched Opx-Cpx analyses. In many cases, we could not obtain contextual information of whether the analysis was taken at a core or rim. A notable exception is the data of Streck and Leeman, (2018) who overlay their measurements on thin section images. One problem with literature compilations of mineral compositions is that a number of published analyses are labelled as Cpx are actually Amp or Opx or vice versa. To automatically sort through these, we use a sklearn support vector classification machine learning algorithm (linear kernel) trained on a compilation of pyroxenes, feldspars, amphiboles, apatites, olivines and oxides. Analyses classified as pyroxenes are further filtered to only use analyses with cation sum between 3.95 and 4.05, and Ca/(Ca+Mg+Fe) ratios between 0.2 and 0.5 for Cpx and 0–0.06 for Opx (excluding pigeonites). We filter out Amp with cation sums outside of 15–16. All thermobarometry and filtering calculations were performed using the open-source Python3 tool Thermobar (Wieser et al., 2022).

Cpx-based barometry in the Cascades has utilized a variety of models to convert measured phase compositions into pressures (and temperatures). Hollyday et al. (2020) and Scruggs and Putirka (2018) use the Cpx-Liq barometry of Neave and Putirka (2017) iterated with the Cpx-Liq thermometer of Putirka (2008, eq33). Sas et al. (2017) use the Cpx-Liq barometer from Putirka (2008, eq32c) with an unspecified thermometer. However, applying different Cpx-Liq barometery equations to the same Cpx-Liq pairs yield pressures that can differ by 3–12 kbar (~10–45 km, see Wieser et al., 2023b), which is an offset equivalent to the entire thickness of the Cascade crust (~10–45 km, Das and Nolet, 1998). Additionally, Cpx-Liq barometry relies on identifying or reconstructing a liquid composition in equilibrium with each Cpx composition (Scruggs and Putirka, 2018), which is challenging in arcs where whole-rock compositions may not necessary represent true liquids (Kent et al., 2010) and many equilibrium tests perform badly (Wieser et al., 2023b). Given that Cpx-only and Cpx-Liq barometers show similar performance for a dataset of arc-like experimental products (Wieser et al., 2023b), we avoid melt-matching complications by using the Cpx-only barometers of Jorgenson et al. (2022, hereafter J2022) and Wang et al. (2021 eq1, hereafter W2021). These two Cpx-only barometers show the best RMSE and R^2 values (J2022: R^2=0.78, RMSE=1.9 kbar, W2021: R^2=0.66, RMSE=2.4 kbar) and least systematic error when applied to the ArcPL experimental dataset consisting of several hundred experiments relevant to arc magmas conducted at 0–17 kbar which were not used in model calibration (Wieser et al. 2023b). These RMSE mean that these two Cpx-only barometers can identify magma storage depths within a window spanning ~15–18 km at 1σ confidence. The relatively thick crust in the Cascades (~40–50 km, Jiang et al., 2023; Kiser et al., 2016; Parsons et al., 1998; Shehata and Mizunaga, 2022) means that Cpx-based barometry can roughly distinguish between storage in the upper, mid and lower crust at best. Another advantage of these two barometers is that they are independent of temperature and H_2O content, which are difficult to estimate from Cpx compositions alone (Wieser et al., 2023b). An additional complication with literature compilations is that the quality of mineral analyses in our compilation is not known, as publications do not quote the analytical precision of each measurement. Analytical uncertainty related to the measurement of Na_2O in pyroxene can easily yield errors spanning 3–5 kbar on each individual Cpx measurement (Wieser et al., 2023a). Averaging multiple Cpx compositions at each volcano can help to mitigate these random analytical errors (Putirka et al., 1996), and results in a substantial improvement when applied to the experimental data investigated by Wieser et al. (2023b). Thus, we predominantly focus on median pressures calculated for each volcano.

Identifying equilibrium Amp-Liq pairs is even more challenging than for Cpx-Liq, because the only widely-used equilibrium test to assess equilibrium is the exchange of Fe-Mg ($K_{D\ Fe\text{-}Mg}$). Tests on experiments in the ArcPL dataset not used to calibrate the Amp-only barometer of Ridolfi (2021, hereafter R2021) performs moderately well (RMSE=2.7 kbar, R^2=0.67), as long as extreme care is taken to ensure that the barometer is being used within the P-T-X limits of the calibration (Wieser et al., 2023c). When displaying Amp-only pressures, grey kernel distributions and black crosses show amphiboles that pass the compositional filters of Ridolfi (2021, Fig. 2–12). We also apply an additional filter to remove Amp with atomic proportions on the basis of 13 cations >6.8 for Si, and <1.1 for Al, which lie outside the calibration range of the Ridolfi model (these filtered pressures are shown with a green kernel distribution and grey crosses, Fig. 2–12, see supporting Fig. S1–2). In general, these two additional filters remove Amp with the lowest calculated pressures, pushing the median pressure substantially deeper. A large number of Amp at Lassen (N=260, Fig. 2) are excluded using this filter, affecting the interpretation of magma storage, but at other volcanoes this filter has a minor influence on the median pressure.

For Cpx-Opx, we calculate pressures by iterating Putirka (2008) eq36(T)-eq39(P) and eq37(T)-eq39(P). Using a new dataset of arc mineral and liquid compositions not used to calibrate such models (Wieser et al., 2023a, 2023b) we find that these two-pyroxene barometers behave poorly for Cpx with Mg#<0.68, so we filter out such pairs. Even for Mg#>0.67, it should be noted that Cpx-Opx barometry has a large RMSE (3.7-4.1 kbar).

Blundy (2022) released a liquid-only thermobarometry method to calculate temperature, pressure and fluid composition (X_{H2O}) from the composition of a liquid saturated in Cpx-Amp-Opx-Plag-Magnetite-Ilmenite (CHOMPI). They examine experiments specific to Mount St. Helens, and produce an empirical expression which can be used more generally to obtain the conditions of storage of CHOMPI-saturated magmas. They apply this method to the youngest rocks erupted from 16 Cascade volcanic centers. However, no independent test dataset was used by Blundy (2022) to assess the performance of this model, and the influence of false positives was not widely assessed (e.g., the algorithm classifying the liquid as CHOMPI-saturated when it was not). By coding CHOMPI into Python3 (available in Thermobar, Wieser et al. 2022a), we are able to perform such independent tests. Using the same criteria Blundy (2022) use for the Cascades, CHOMPI calculations in Thermobar returned a false positive rate of ~46%, and a very poor relationship between experimental and CHOMPI pressure (Fig S3, see Text S1, Fig. S3). Thus, we do not discuss the results from this method further.

We also compile experimental constraints where directly relevant to a specific Cascade edifice. We quote these pressures as published.

Melt inclusion saturation pressures

Solubility models can be used to estimate the pressure at which a melt with a given major element composition, volatile content and temperature becomes volatile-saturated. Thus, assuming a melt inclusion was trapped from a volatile-saturated magma, the pressure at the time of melt inclusion entrapment can be calculated. However, Cascade MI studies have used a wide variety of solubility models (see Supporting Table S1). Because the calibration datasets of many of these models span a limited compositional range, calculated saturation pressures can easily differ by a factor of two or more (Wieser et al., 2022b). Thus, the use of different models at different volcanoes adds considerable uncertainty when comparing depths determined from different research groups over different time periods, both of which influence the choice of model. For consistency, we use published major element and volatile contents to recalculate all saturation pressures using the solubility model MagmaSat implemented in the Open-source Python3 tool VESIcal (Iacovino et al., 2021); Wieser et al. (2022b) show that this model best recreates experimental data for andesitic and dacitic compositions, and has the largest calibration dataset of all available models.

MI saturation pressures have other limitations. If crystals are growing and trapping melt inclusions during storage in the crust, the distribution of melt inclusion saturation pressures will reveal the main magma storage regions. However, melt inclusions can also form during ascent towards the surface, because degassing of H_2O is often accompanied by crystallization (Applegarth et al., 2013; Lipman et al., 1985). This can result substantial 'smearing' of saturation pressures towards shallower pressures. It is also becoming increasingly apparent from Raman spectroscopic analyses that a large proportion of the total CO_2 in a MI is held within the vapour bubble in olivine-hosted MIs in arc magmas (e.g. Mironov et al., 2020; Moore et al., 2018, 2015). Accurate Raman measurements require each laboratory to carefully determine the relationship between Raman spectral features and CO_2 densities using an optical apparatus where CO_2 gas is held at varying pressure conditions and temperature is closely controlled (DeVitre et al., 2021; Lamadrid et al., 2017), or reference materials are obtained from a laboratory where they were measured with an optical apparatus (e.g., Mironov et al., 2020, Wieser et al., 2021). Only the MI vapour bubbles from two cinder cones near Lassen Peak by Aster et al. (2016) have been measured on a calibrated Raman system. Venugopal et al. (2020) perform Raman measurements but use a literature calibration line rather than an instrument-specific calibration. The large number of their bubbles measured at room temperature with reported CO_2 densities above the thermodynamical limit indicates that their calibration may have overestimated CO_2 densities (DeVitre et al., 2023). Other studies reconstruct vapour bubbles using bubble growth models (Johnson and Cashman, 2020; Walowski et al., 2019). However, these reconstructions require a precise estimate of the amount of post-entrapment crystallization (PEC) experienced by MIs, which in turn, requires accurate estimates of the initial FeO_t content of each MI (Danyushevsky and Plechov, 2011). Estimating initial FeO_t is very challenging for monogenetic cones, where the fractionation path is uncertain because only a very narrow range of liquid compositions were erupted. The remaining studies of olivine-hosted MIs do not measure or reconstruct the vapour bubble (e.g. Ruscitto et al., 2010; Walowski et al., 2016). As a result, saturation pressures obtained from published MI data must be interpreted with extreme caution, due to uncertainty regarding total CO_2 contents.

To obtain a self-consistent database, we calculate saturation pressures using bubble CO_2 from Aster et al. (2016) for MI saturation pressures, and bubble + glass reconstructions from Venugopal et al. (2020), with the important caveat that the Venugopal et al. (2020) Raman measurements may have overestimated CO_2 because of the absence of an instrument-specific calibration. We do not use modelled bubble reconstructions, because of the wide variability of different approaches used, and the sensitivity of these methods to reliable estimates of the amount of PEC, H_2O-loss etc, which we do not have sufficient data to reliably estimate for many datasets. Thus, it is important to recognise that the pressures shown for the mafic MI from studies other than Aster et al. and Venugopal et al. are very much minimum estimates, and the pressures would likely increase dramatically if bubble CO_2 were accounted for. For more silicic melt inclusions, it is very difficult to assess the possible influence of the vapour bubble, given a lack of available measurements globally.

Trends at a single volcano

Ideally, we would look at trends in magma storage through time at each volcano, and variations in storage as a function of magma chemistry. Where possible, we split data by major volcanic phase (e.g., Fig. 2 – Lassen domefield vs. Brokeoff Volcano). We also indicate the mineral hosting melt inclusions (e.g., Ol-hosted melt inclusions indicate storage of the most mafic magmas, Qtz-hosted the most silicic). Determining the relationship between storage and magma composition is particularly challenging with Cpx and Amp barometry. Given that magma mixing is ubiquitous in the Cascade arc, minerals were erupted in a silicic magma cannot be assumed to have grown in that composition magmas (and vice versa for minerals erupted in a mafic magma). In Figs. S3–S8, we show Cpx barometry results plotted against Cpx Mg# and grouped by study. No robust trends appear, although there is a possible hint that the most mafic magmas are indeed stored deeper. We show using experimental data that calculating liquid compositions from Amp to compare to pressures generates spurious trends, because similar Amp components are used to calculate chemistry and pressure (Supporting Fig. S4). Detailed work at each edifice would be required to resolve differences in magma storage as a function of magma chemistry that are not apparent in our literature compilation.

Calculating depths and reconciling different reference levels

Melt inclusion saturation pressure and mineral barometers yield pressures, which are then converted to depths (H) using assumptions about crustal density (e.g., $P=\rho gH$, or a crustal density model). Cascade MI and thermobarometry studies have used a wide variety of crustal densities to convert pressures into depths in the crust (ρ=2200 kg/m^3 by Bacon et al., 1992, ρ=2700 kg/m^3 by Hollyday et al., 2020, ρ=2800 kg/m^3 by Johnson and Cashman, 2020, ρ=2200 kg/m^3 for the first 2 km and ρ=2800 below that by Gardner et al. 1995). Here, we convert pressures to depths using a uniform crustal density of ρ=2700 kg/m^3.

In contrast, geophysical methods generally determine depths relative to a variety of reference levels. We abbreviate these as: below sea level (bsl), below ground level (bgl), below average station level (basl), or reference level unknown (rlu). When comparing geophysical depths to one another, and to petrological estimates, it is important to account for different reference levels. For consistency, we adjust all measures to yield depth below the summit of each volcano. This means that geophysical estimates will match petrological estimates if the magma chamber is centrally-located. However, given evidence for magma reservoirs being offset from the volcanoes summit (Lerner et al. 2020), this correction could lead to a systematic offset between petrological and geophysical estimates. To allow visual assessment of these possible offsets, we include a topographic profile across each major edifice on each diagram, extracted from the ASTER global digital elevation model V003 using QGIS (NASA/METI/AIST/Japan

Space systems And U.S./Japan ASTER Science Team, 2019; QGIS.org, 2022). Petrological and geophysical estimates could be displaced from one another by a vertical distance equivalent to the maximum height of the topographic profile.

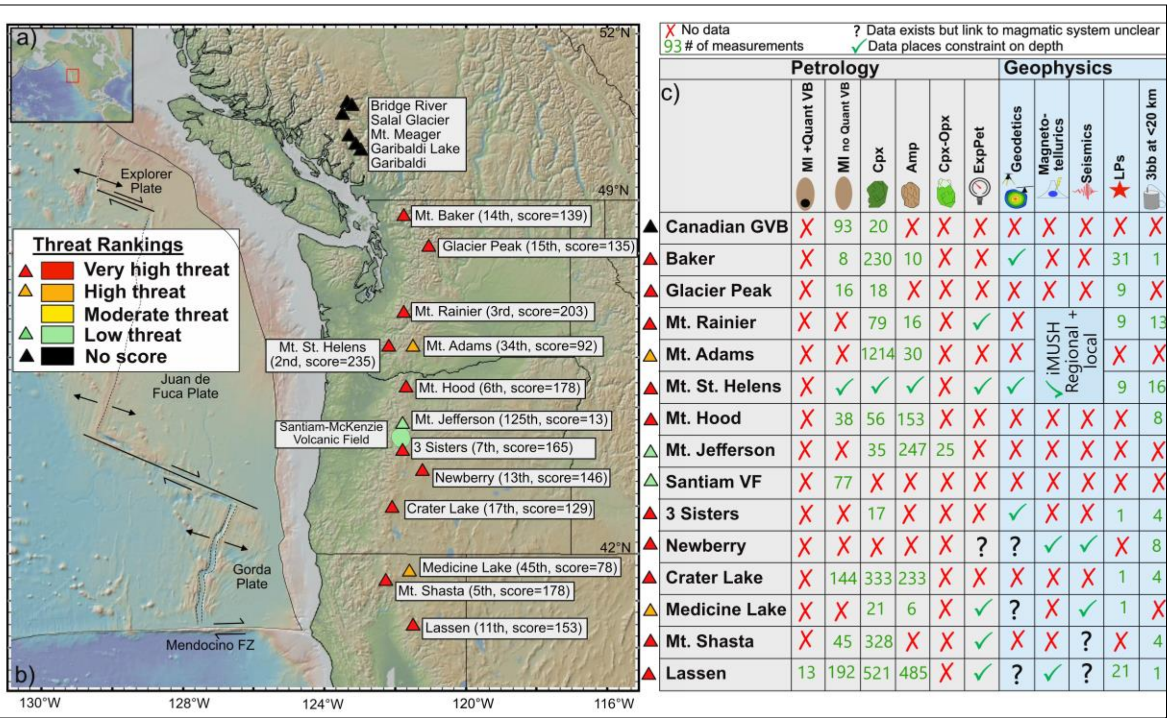
Seismic data coverage

To obtain the km-scale resolution required to image magma bodies using seismic or magnetotelluric methods, it is normally necessary to obtain data using short-term high-density array deployments (e.g., Bedrosian et al., 2018; Kiser et al., 2018; Zucca and Evans, 1992). At relatively well-monitored volcanoes such as Mount Rainier and Mount St. Helens, these arrays can be used in conjunction with permanent volcano-monitoring networks (e.g., Moran et al., 1999; Ulberg et al., 2020; Waite and Moran, 2009). To help conceptualize the evolution in the quality and amount of seismic data available at different volcanoes, we plot the position of seismometers within ~20 km (0.18˚) of the summit of each major edifice. We display this data on a map and a timeline for each major US Cascade volcano (Fig. 2–14). The underlying station metadata was pulled from the IRIS GMAP server (http://ds.iris.edu/gmap/) and the Pacific Northwest Seismic Network (PNSN) compilation (https://pnsn.org/seismograms/map, both updated, Sept 5th, 2022, http://ds.iris.edu/gmap/). We classify stations based on their station code as 1 component short period (1sp), 3 component short period (3sp) or 3 component broadband (3bb). Short-period stations are often older, analog-telemetered with limited dynamic range. Waveform-based measurements (such as ambient noise tomography, receiver functions, attenuation measurements) tend to be challenging using this data. Those stations are most useful for local earthquake travel-time tomography (e.g., Moran et al., 1999). Newer broadband stations, generally installed in the mid-late 2010’s, provide more imaging options.

As permanent monitoring networks are densified and older 1– or 3–component seismometers are replaced with modern broadband seismometers, the potential for a new generation of imaging using only permanent installations increases (both through increased station density, and the potential for wavefield-based imaging methods using broadband data). For example, broadband data enables ambient-noise imaging, which provides high-accuracy estimates of shear-wave velocity (Vs) at the upper-crustal depths where magma storage frequently occurs (e.g., Crosbie et al., 2019; Jiang et al., 2023). We also summarize the presence and depth of Deep Long Period earthquakes (DLPs, Nichols et al., 2011), although exactly how these signals relate to the volcanic plumbing system is still enigmatic.

Results

Data coverage varies widely along the Cascades (Fig. 1–15). Some edifices such as Mount St. Helens have an abundance of petrological and geophysical studies using a variety of methods (seismics, magnetotellurics, geodetics, Fig. 10). Some volcanoes are relatively well studied using one method but not the other (e.g., very little petrology but moderate to good geophysical coverage at Newberry and Mount Rainier, Fig. 7, Fig. 12), while other volcanoes have very little data from either method (e.g., Three Sisters, Glacier Peak, Fig. 6, Fig. 13). The variability of available data reflects a combination of the heavy focus of research efforts on certain volcanoes (particularly for petrology), quiescence or noisy geophysical signals at certain centres (Poland et al., 2017), and often-insurmountable issues associated with permitting any monitoring equipment within protected wilderness areas and parks (Moran and Benjamin, 2021). It is interesting that there is no apparent correlation between the estimated threat level or ranking out of all US volcanoes and the availability of data (Ewert et al., 2018. Fig. 1).



X No data
93 # of measurements
? Data exists but link to magmatic system unclear
✓ Data places constraint on depth

c)	Petrology						Geophysics				
	MI +Quant VB	MI no Quant VB	Cpx	Amp	Cpx-Opx	ExpPet	Geodetics	Magneto-tellurics	Seismics	LPs	3bb at <20 km
▲ Canadian GVB	X	93	20	X	X	X	X	X	X	X	X
▲ Baker	X	8	230	10	X	X	✓	X	X	31	1
▲ Glacier Peak	X	16	18	X	X	X	X	X	X	9	X
▲ Mt. Rainier	X	X	79	16	X	✓	X	✓ iMUSH Regional + local		9	13
△ Mt. Adams	X	X	1214	30	X	X	X			X	X
▲ Mt. St. Helens	X	✓	✓	✓	X	✓	✓			9	16
▲ Mt. Hood	X	38	56	153	X	X	X	X	X	X	8
△ Mt. Jefferson	X	X	35	247	25	X	X	X	X	X	X
△ Santiam VF	X	77	X	X	X	X	X	X	X	X	X
▲ 3 Sisters	X	X	17	X	X	X	✓	X	X	1	4
▲ Newberry	X	X	X	X	X	?	?	✓	✓	X	8
▲ Crater Lake	X	144	333	233	X	X	X	X	X	1	4
△ Medicine Lake	X	X	21	6	X	✓	?	X	✓	1	X
▲ Mt. Shasta	X	45	328	X	X	✓	X	X	?	X	4
▲ Lassen	13	192	521	485	X	✓	?	✓	?	21	1

Figure 1 – Schematic diagram showing the available barometric constraints along the Cascade arc. The locations of the major volcanoes from the USGS Holocene catalog (Hildreth, 2007) are overlain on a GeoMapApp base image (Ryan et al., 2009) with triangles colored by the USGS threat rankings. The numbers show the threat score and threat rank out of 161 US volcanoes included in the assessment (1st being the most hazardous). The Santiam-Mckenzie volcanic field is not given a score, but the report says that it has a similar threat level to the individual low-threat centers (Blue Lake, Belknap etc). The table schematic shows the availability of different types of data at each volcano. 3bb is the number of broadband seismometers within 20 km.

Lassen Volcanic Center

Activity at Lassen Volcanic Center is subdivided into three main eruptive stages: 1) the Rockland Caldera Complex (825 – 609 ka), 2) Brokeoff Volcano (590 – 385 ka), and 3) the Lassen domefield (~300 ka to present, Clynne et al., 2008). Three dominant Holocene eruptions have occurred during the Lassen domefield stage; Chaos Crags (~850 AD, Clynne et al., 2008), Cinder Cone (1666 AD, Sheppard et al., 2009), and Lassen Peak (1914–1917 AD; Clynne, 1999). There are also abundant mafic cinder cones within the Lassen segment of the Cascades, with both calc alkaline and tholeiite compositions (Walowski et al. 2019).

Mineral Compositions: Unpublished Cpx compositions were obtained from M. Clynne and B. Platt for samples from a range of formations from Brokeoff Volcano as described in Bullen and Clynne (1990) and Clynne et al. (2008). These include andesites from the Diller sequence (470–385 kyrs ago, e.g., Rice Creek, Mount Diller) and the Mill Canyon sequence (470–590 kyrs, Clynne and Muffler, 2010). Platt (2020) measured core-rim traverses for Cpx crystals from Brokeoff Volcano. We extract core and rim compositions from these profiles, except for the longest traverses, where we extract core, intermediate and rim analyses for Cpx-only calculations.

Underwood et al. (2012) analyse Amp from the several Lassen domefield stage eruptions for hydrogen isotopes, water contents and ferric/ferrous ratios and major elements which we use for Amp-only barometry (N=316). These units represented by these analyses are the ~35 ka Kings Creek unit, 28.3 ka dacite dome on Lassen Peak, 850 AD Chaos Crags, and 1914–1917 AD Lassen Peak.

Hollyday et al. (2020) perform Cpx-Liq thermobarometry calculations on samples from a cinder cone from the basaltic-andesite of Box Canyon (middle Pleistocene age). They combine N=20 core analyses with a primitive MI composition from the basalt of Big Lake (BBL) from Walowski et al. (2016), and obtain pressures of 460–700 MPa using the Cpx-Liq barometer of Neave and Putirka (2017). However, we were not able to obtain the exact liquid composition used by the authors and could not recreate these pressures. Considering all PEC-corrected MIs from BBL, we instead obtain pressures distributed between -0.5 to ~2.5 kbar (regardless of the exact equilibrium tests used). This discrepancy makes the inference from Hollyday et al. (2020) of lower crustal storage difficult to validate.

Overall, Cpx-only barometry using W2021 yields median pressures of ~0.6 kbar for Brokeoff volcano, and ~1.9 kbar for the Lassen domefield. Pressures using J2022 are slightly deeper compared to W2021 for both formations (median=1.4 kbar for Brokeoff, 2.6 kbar for the domefield). These deeper pressures likely result from the fact that extra-tree regression strategies used by J2022 never yield negative numbers, skewing averages towards anomalously high pressures. If Amp-only pressures are calculated using just the filters of Ridolfi (2021), the median pressure is 1.2 kbar. However, if we also discard amphiboles with Al and Si cation fractions outside the range of the calibration dataset, we obtain substantially higher pressures (3.2 kbar). We favour the deeper, more extensively filtered median pressures (~3.2 kbar), as none of the experiments used to calculate the R2021 barometer were performed at <1.3 kbar. Overall, considering the errors on these methods, Amp- and Cpx-only barometry are broadly consistent with magma storage in the upper ~0.5 to 4 kbar of the crust at Lassen Volcanic Center. It is possible that a small number of erupted minerals originated deeper, but this is hard to distinguish from uncertainty given the lack of analytical metadata (Wieser et al. 2023a).

Melt inclusions: The majority of melt inclusion measurements in mafic samples have focused on the cinder cones surrounding Lassen, rather than the main edifice. Saturation pressures may be representative of the storage depths of the most mafic magmas supplied to the edifice. Aster et al. (2016) analyse olivine-hosted MIs from two cinder cones near Lassen (Basalt of Round Valley Butte - BRVB, and Basalt of old Railroad Grade – BORG), measuring CO_2 and H_2O in the melt phase using FTIR, and performing the first measurements of vapour bubble CO_2 in the Cascades using Raman Spectroscopy. The limited number of MIs where both the bubble was measured, and the MI was large enough for FTIR analyses means that there are only N=9 analyses from BORG and N=4 analyses from BRVB where both phases were directly measured in the same inclusion. In addition to direct Raman measurements, Aster et al. (2016) produce a model to reconstruct vapour bubble CO_2, tracking the volume of a growing vapour bubble during post-entrapment crystallization using volume and density information from crystallization simulations in rhyoliteMELTS (Gualda et al., 2012). The composition of the vapour phase in the modelled bubble volume was then calculated using the solubility model of Iacono-Marziano et al. (2012). While there is a broad correlation between modelled and reconstructed vapour bubble CO_2 contents when all samples are considered (Cascades, Parícutin, and Jorullo), the correlation for Lassen samples is poor (R^2=0.01, gradient = 0.09). Model-reconstructed values both over and underestimate the amount of CO_2 measured by Raman spectroscopy, and there is no clear association between this discrepancy and whether the bubble contained carbonates. We suggest that discrepancies between Raman measurements and models may result from large uncertainties in determining the exact amount of post-entrapment crystallization experienced by each MI (which controls the calculated bubble volume), as well as the quench rate, and the amount of H_2O loss. The reconstructions of Aster et al. use Petrolog3 to perform post-entrapment crystallization corrections, which requires the user to estimate the initial FeO_t content of each MI, a quantity that is very challenging to estimate in volcanic fields/systems where there is no single liquid line of descent. This is particularly true at Lassen, where different eruptive centres have a wide range of FeO_t contents at similar MgO contents (Clynne, 1999). Thus, we do not calculate pressures for the Aster et al. (2016) MIs where they reconstruct the bubble using their model, and only consider those where the bubble was directly measured by Raman spectroscopy.

Walowski et al. (2016) perform FTIR measurements of olivine-hosted MIs (N=115) from a wide variety of Quaternary cinder cones in a large volcanic field surrounding Lassen Peak. Walowski et al. (2019) perform FTIR measurements of olivine-hosted MIs from the 1666 CE eruption of Cinder Cone. Neither study performed direct vapour bubble CO_2 measurements, but Walowski et al. (2019) performed reconstructions using the method of Aster et al. (2016). Specifically, they calculated the amount of PEC assuming an initial FeO_t content of 7 wt%. However, as described above, a similar method perform poorly for the Lassen samples of Aster et al. (2016), and is very sensitive to the amount of PEC (and thus the initial FeO_t content of the melt inclusion). Cinder Cone lavas and tephra samples have FeO_t contents ranging from 5.5–7 wt%. Using Petrolog3, MI LCC-9–OL-01 has experienced 9.9 wt% PEC if reconstructed to 7 wt% FeOt, but only 2.8 % PEC if reconstructed to 5.5 wt% FeO (most MIs have differences of 6–7 % PEC). The resulting change in temperature (ΔT), and therefore the volume of the bubble, and the total mass of bubble CO_2, is 2.5x less if FeOt is set at 5.5 wt% vs. 7 wt%. Given the large uncertainties associated with bubble reconstructions, we only show measured H_2O-CO_2 contents for Walowski et al. (2016, 2019) MIs, with the caveat that they are very much minimum estimates.

When all MI saturation pressures are recalculated using MagmaSat (Ghiorso and Gualda, 2015), the measurements of Aster et al. (2016) yield pressures spanning 1.4–5.5 kbar. Melt-only saturation pressures from Walowski et al. (2016, 2019) are significantly shallower, as expected, and are likely not a useful constraint on magma storage.

The only melt inclusion constraint on storage beneath the main edifice comes from FTIR analyses of Qtz-hosted MIs from the Chaos Craggs rhyodacite by Quinn (2014). Discarding MIs with <3 wt% H_2O which they suggest have undergone leakage, leaves 34 MIs, which yield pressures of ~1–2 kbar. Vapour bubbles are not mentioned in this study, so it is difficult to assess the impact of bubbles on CO_2 contents. If these vapour bubbles are CO_2-poor, these results may indicate that more evolved magmas are stored at shallower depths than the regional basaltic magma supply examined by Aster et al. (2016).

Experimental Petrology: Schwab and Castro, (2007) perform H_2O-saturated experiments to determine pre-eruptive storage conditions for the dacitic pumice erupted in 1915 from Lassen Peak. Comparison of natural and experimental products indicate that the dacitic magma equilibrated at 0.5 kbar and 800–875˚C prior to mixing with an andesitic end member. Quinn (2014) perform H_2O-saturated experiments to assess the pre-eruptive storage conditions of the rhyodacitic magma erupted at Chaos Crags. By comparing textures and phase assemblages in natural samples with experimental products, they infer that the most probable conditions of magma storage for these silicic magmas were 1.45±0.25 kbar and 770±10˚C.

Geophysics: The first geophysical interpretation of magma storage under Lassen Volcanic Center came from Benz et al. (1992), who used teleseismic P wave arrival times to investigate lithosphere structure in northern California. They invoked a low-velocity zone (average -7.2%) beneath Lassen Volcanic Center (as well as Medicine Lake) within Layer 1 of their model, which spans 0–15 km depth. More precise depth estimates cannot be obtained from such teleseismic models. However, the low is displaced 30–50 km NE from Lassen, and extends to depths of 70 km, perhaps as an artifact of vertical smearing (Thurber et al., 2009). Park and Ostos (2013) show P-wave tomography from an MSci thesis (Reeg, 2008) investigating measurements conducted using the Sierra Nevada EarthScope project (2005–2007) which imaged a 600 km x 150 km area, with Lassen National Park in the north. They identify a low velocity zone, although they cannot determine whether it is a mantle or crustal feature based on the wide station spacing (Park and Ostos, 2013). Overall, these teleseismic studies do not have sufficient resolution to reliably image small crustal magma chambers beneath Lassen Peak.

Park and Ostos (2013) examine a 250–km long broadband and long period magnetotelluric line "LASS" along the 40.5˚N parallel. This survey line passes 20 km north of Lassen Peak (40.488 ˚N). No large crustal conductor was observed beneath Lassen Peak, supporting our assertion that the teleseismic studies described above cannot provide useful constraints on upper crustal magma storage. However, they do identify three small conductors within the Lassen Volcanic Center at ~15–30 km (rlu, presumed bsl), which they suggest are basaltic reservoirs that may heat and melt the lower crust.

Another possible constraint comes from a compilation of the depths of earthquakes recorded from 1984 to 2016 (see Fig. 6b of Taira and Brenguier, 2016). These depths show a prominent peak at ~4–6 km (rlu). Such high-frequency or volcano-tectonic earthquakes require brittle (velocity-weakening) conditions, indicating temperatures far below the solidus, and are usually seen at a few km from sites of eruption (e.g., White and McCausland, 2016). The simplest interpretation is that the main magma storage region must be deeper than this high-frequency seismicity.

Pitt et al. (2002) report the depths of N=20 long-period earthquakes ranging from ~12–27 km depth (basl), which may represent magma recharge (indicating that the main magma storage region is above these). The absence of further seismic constraints at Lassen results from the fact that the permanent network is very small (Fig. 2f-g), and that no high-resolution study has even been performed in the region.

Unfortunately, geodetic measurements at Lassen Volcanic Center do not help constrain magma storage depths. Lassen Volcanic Center has experienced broad, regional subsidence since 1992, consistent with a point source at ~ 8 km depth. However, the source of this subsidence is unclear, with dominant contributions likely from regional extension, changes in the location of hydrothermal/magmatic fluids, and a possible minor influence of the cooling and crystallization of a magma body (Parker et al., 2016; Poland et al., 2004). Regional GPS will likely be vital to deconvolve the relative role of crustal extension compared to hydrothermal and magmatic processes. Given the ambiguity, we do not include this deformation source on Fig. 2.

Summary and future work: Cpx-only and Amp-only barometry, Qtz-hosted MI saturation pressures, and available experimental constraints indicate that the majority of magma storage surrounding Lassen is within the upper crust (<4 kbar, <15 km). These depths are not inconsistent with the distribution of shallow earthquakes thought to overly the magma chamber, but further geophysical constraints from short-term high-density arrays, and/or the addition of more broadband seismometers providing an opportunity for passive-source tomography, would help to confirm the location of the shallow magma reservoir. Based on the downward spread of Cpx-only and Amp-only pressures, the presence of higher saturation pressures from Aster et al. (2016), and the seismic results of Park and Ostos (2013), further work is certainly needed to investigate whether there is deeper magma storage of more mafic magmas. This could be targeted through a study focusing on vapour bubble CO_2 in a large suite of melt inclusions, experiments on relevant starting compositions, or a local high resolution seismic survey.

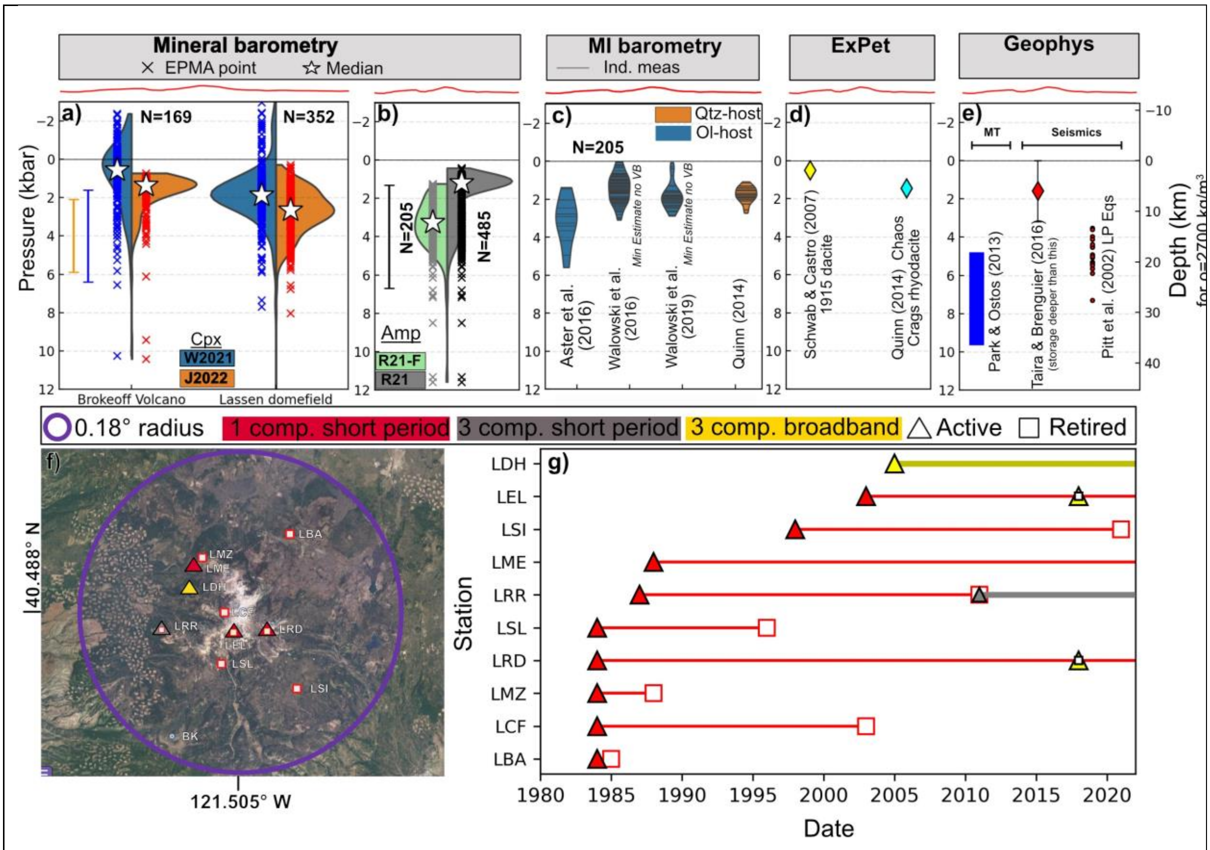


Figure 2**: Compilation of magma storage depths at Lassen Volcanic Center (a-e) and summary of the seismic network (f-g).** Violin plots show the distribution of pressures estimated from Cpx and Amp barometry, with individual pressures shown as crosses, and the median pressure shown with a white start. We overlay the ±RMSE of each barometry method estimated using a dataset of arc magmas not used in model calibration (Wieser et al. 2023b,c). The depth axis on a-e) is relative to the volcanoes summit. The red profile shows the height above sea level (the top of the chart) across a W-E section spanning 15 km section transecting the summit. As we could not obtain the exact earthquake catalog used by Taira and Brenguier (2016), we show the peak of their histogram ± the

minimum and maximum values present with error bars. Magma is likely stored deeper than these earthquakes (red diamond). f) Map of seismic stations within 0.18˚ (~20 km) of Lassen Peak's summit. g) Schematic showing seismic station types vs. time (lines changing color show station upgrades), within a circle with radius of 0.18° of the latitude and longitude shown on f). Data from IRIS.org.

Mount Shasta

The position of Mount Shasta west of the Cascade arc axis and only ~70 km above the subducting plate means that it could be considered a fore-arc volcano (Christiansen et al., 2017; McCrory et al., 2012). Mount Shasta is a composite edifice, mostly comprised of five cones (Sand Flat, Sargents Ridge, Misery Hill, Hotlum and Shastina, Christiansen et al., 2020) which have a primarily calc-alkaline, high-silica-andesitic to low-silica-dacitic composition (60–67 wt% SiO_2). Quenched mafic inclusions of more MgO-rich magma are common. The last 10 kyr of eruptive history at Mount Shasta indicates that eruptions occur every 600–800 years, with the most likely hazards being ash, lava flows, domes, pyroclastic flows and debris flows (Christiansen et al., 2017; USGS, 2022). Tephra is rare, with most pyroclastic deposits resulting from dome collapse (Christiansen et al., 2020). In addition to the main volcanic edifice, Mount Shasta is surrounded by a number of basaltic-andesite to andesitic shields (Ash Creek Butte, The Whaleback, Deer Mountain, Miller Mountain etc.), and less common basaltic to basaltic-andesitic cinder cones (Christiansen et al., 2017). While the majority of erupted material has a more evolved composition, small amounts of primitive magnesian andesite (PMA), high magnesian andesite (HMA) and high-alumina olivine tholeiite (HAOT) with high Mg#s are found in cinder cones and on Mount Shasta's flanks (Christiansen et al., 2013).

Mineral Compositions: Recent petrological work around Mount Shasta has largely focused on the HMA erupted at the S17 cinder cone near The Whaleback, ~20 km NNE of the main edifice. Interest in this cinder cone reflects a long-standing debate over whether HMAs are near primary mantle melts (Baker et al., 1994; Barr et al., 2007; Grove et al., 2002) or the result of magma mixing and crustal contamination (Streck and Leeman, 2018). Streck and Leeman (2018) display their EPMA data in an interactive tool overlain on a BSE image, allowing us to identify pairs of EPMA points on touching Opx-Cpx pairs. We assess all possible combinations of Cpx-Opx analyses for touching grains (e.g., for three EPMA spots on a Cpx, and two for a touching Opx, we obtain six pairs). This yields a total of N=122 pairs. We also manually extract N=328 Cpx analyses where the location in the crystal could be classified (Core, Rim). Phillips and Till, (2022) measure Cpx and Opx compositions from the same HMA S17 cinder cone, although from the data it is not possible to distinguish which analyses represent touching pairs. Given there is only one equilibrium test for Cpx-Opx (K_D, Fe-Mg) which shows limited success for hydrous experiments (Wieser et al., 2023c), we do not consider pairs when the textural context is unknown. Cpx-only pressures from these HMA are highly variable, ranging from 1–6 kbar (with very similar distributions and medians for J2022 and W2021). Cpx-Opx pressures are offset ~2–3 kbar deeper, but certainly overlap with the distribution of Cpx-only pressures (particularly given the 3-4 RMSE on each method, Wieser et al. 2023c).

Baker et al. (1994) perform mineral analyses on a series of basaltic andesite lavas associated with the Sargents Ridge and Misery Hill dome building episodes, located ~15 km to the N and NW of Shasta's summit clustered around Highway 97 (e.g., at ~4000", summit at ~14,000"). They report N=3 representative Cpx compositions. However, M. Baker (written coms) suggest that these analyses were low precision, with the WDS background only being collected once per thin section, so should not be used for barometry. Grove et al. (2005) measure mineral compositions in a wide variety of lavas representing the Hotlum, Shastina, Misery and Sargents eruptive phases from on/around the main Shasta edifice. However only representative mineral composition are reported (a total of N=4 Cpx, N=2 Amp). Given the sparsity of available data, we do not perform any barometry on the main edifice, as these numbers are too small to sufficiently average out random analytical error (Wieser et al., 2023a).

Melt inclusions: Anderson (1974) perform EPMA analyses on olivine-hosted MIs from the S17 cinder cone, calculating H_2O by volatiles by difference. Sisson and Layne (1993) measure glass inclusions from Goosenest volcano and Copco Cone, ~35 km and ~60 km North of Shasta by SIMS. However, because of the lack of glass (and bubble) CO_2 measurements, as well as uncertainties associated with volatile-by-difference methods (see Hughes et al., 2019), we do not calculate saturation pressures for these inclusions.

Le Voyer et al. (2010) perform SIMS measurements of reheated olivine-hosted MIs from H_2O-poor high aluminium olivine tholeiites (HAOTs) and H_2O-rich basaltic andesites from mafic flank eruptions from Mount Shasta. Their measured basaltic-andesite H_2O contents are lower than estimated by Baker et al. (1994), which may reflect diffusive loss from the olivine (adding uncertainty to the saturation pressure). We calculate saturation pressures for the N=25 MIs with major element and volatile data.

Ruscitto et al. (2011) perform FTIR measurements of naturally quenched primitive basaltic andesite and high magnesian andesite olivine-hosted MIs from the S17 cinder cone. We calculate saturation pressures for the N=20 MIs with major element and volatile data. Both datasets yield pressures spanning ~0–2 kbar. However, all Shasta MI studies note the presence of abundant vapour bubbles, many of which remain even after experimental homogenization (Le Voyer et al., 2010). Thus, it is very likely that these calculated saturation pressures are very much minimum estimates for storage of mafic magmas at Mount Shasta.

Experimental phase equilibrium: Grove et al. (2005) compare whole-rock and mineral compositions from the main edifice of Mount Shasta to the experiments of Grove et al. (2003) to infer shallow crustal differentiation of plagioclase (Plag) and pyroxene (Px) in a reservoir at 1–2 kbar (3–6 km, see also Baker et al., 1994). In the schematic model presented in Grove et al. (2005, their Fig. 14), two additional storage zones are depicted: 1) a reservoir fractionating Olivine (Ol)+Px at 7–10 km, and 2) a reservoir fractionating Ol+Amp+Px at 15–25 km (based on high amphibole Mg#s and H_2O-rich MIs). Krawczynski et al. (2012) perform additional experiments at 200, 500 and 800 MPa, and use these experiments to calibrate a barometer estimating P_{H2O} from the highest measured Amp Mg# in a given suite of samples. By applying this equation to Shasta Amps, P_{H2O} values of 2.8–9.5 kbar are obtained. However, these pressures may be significant underestimates if CO_2 is present in the exsolved fluid at depth, such that $P_{tot} \neq P_{H2O}$. Additionally, their Fig. 8 shows that the simple relationship between Amp Mg# and P is more complex in mixed H_2O-CO_2 fluid experiments (and mafic melts beneath Shasta are likely in equilibrium with a mixed fluid).

Geophysics: Thurber et al. (2009) present a regional 3D tomographic model of P wave velocity for all of Northern California using a double-difference tomography algorithm (Zhang et al., 2004) with nodes 15–20 km apart. They image a low velocity zone (~5.5 km/s, 5% reduction) beneath Mount Shasta centred at ~12 km depth (bsl). However, the 40–km horizontal extent of this body makes it impossible to distinguish thermal vs. magmatic contributions to the local velocity low. The lack of high resolution, local seismic inversions reflects the fact that no high density temporary deployments have ever been deployed around Shasta to our knowledge (unlike iMUSH at Mount St. Helens). Additionally, Shasta also shows relatively few earthquakes (Weaver et al., 1990), despite a long-lived short-period monitoring network. This network has been recently upgraded with four three component broadband seismometers (Fig. 3g). Meaningful inversions on this new network will be reliant on recording sufficient earthquakes. From a geodetic perspective, there has been no detectable deformation at Mount Shasta since at least the 1980s (Poland et al., 2017). To our knowledge, there are no other geophysical constraints on magma storage beneath Shasta.

Summary and Future work: Despite the clear hazard potential of the main edifice of Mount Shasta (ranked as the 5th most hazardous US volcano), we have remarkably few constraints on the magmatic plumbing system under the main edifice. While the S17 high magnesian andesite cinder cone is academically interesting from the perspective of the generation of arc magma compositions, this cone has little relevance to future eruptions at Mount Shasta given the relative paucity of these high-magnesian andesite compositions in this volcanic field and its age pre-dating construction of the modern edifice (see Phillips and Till, 2022). We suggest that further work targeting MIs, mineral compositions and phase equilibration experiments in the presence of mixed fluids from the main edifice is needed. From a geophysical perspective, a high-density temporary deployment of seismometers using active sources would help, although permitting would be non-trivial. Soon, we expect sufficient earthquakes to been collected on the upgraded seismic network for a first-order seismicity assessment.

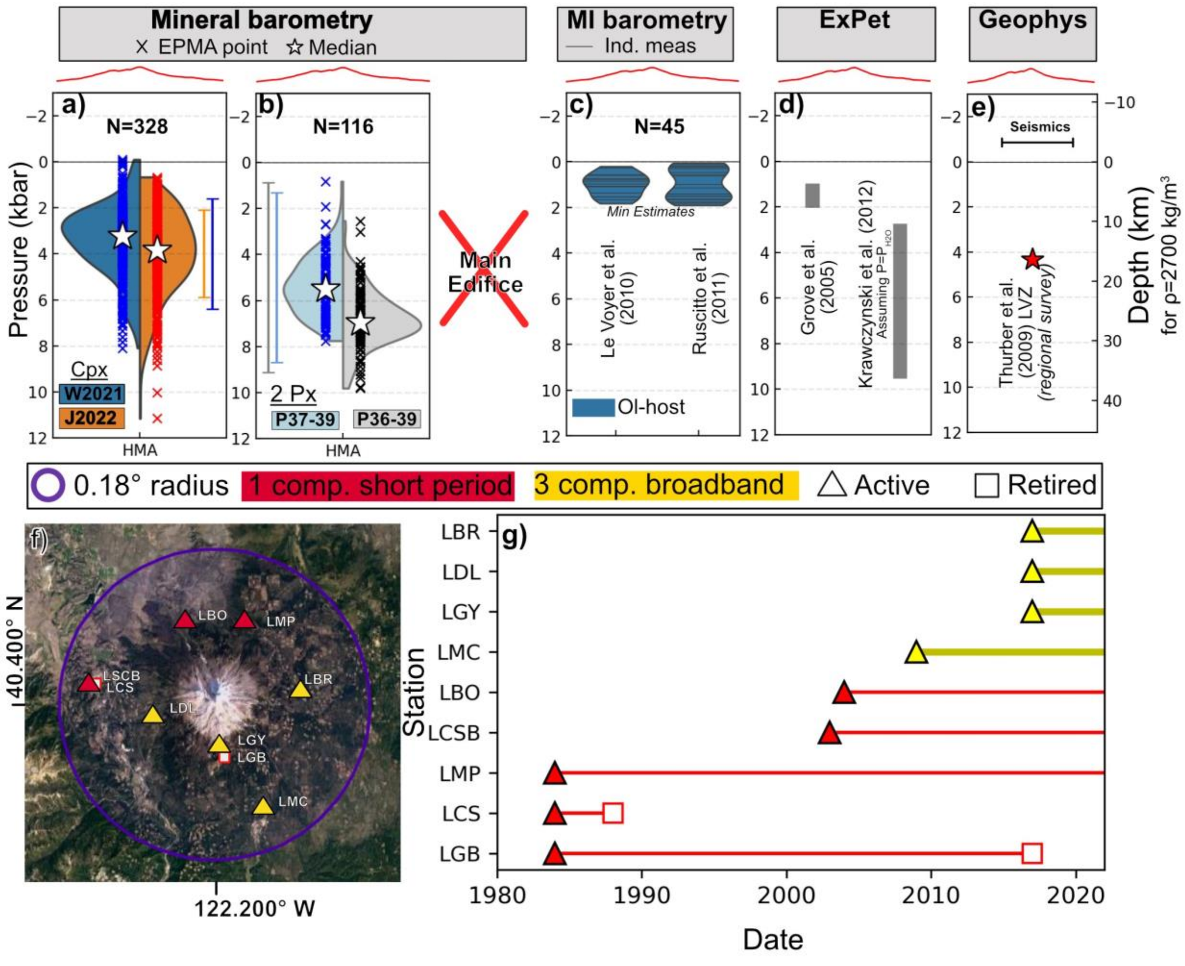


Figure 3 – **Compilation of magma storage depths at Mt. Shasta and the surrounding area (a-e) and a summary of the seismic network (f-g).** Symbols, errorbars and seismic stations as in Fig. 2. The red profile shows the height above sea level across a W-E section spanning 15 km section transecting the summit.

Medicine Lake

Medicine Lake Volcano is located ~50 km E-NE of Mount Shasta and the main Cascade front, on the western edge of the Basin and Range extensional province (Donnelly-Nolan et al., 2008). It has a broad shield shape, and is the most voluminous volcano in the Cascades. It has erupted a wide variety of magma compositions, ranging from hydrous calc-alkaline magmas (basalt to rhyolite), to relatively anhydrous, high-aluminium olivine tholeiites. In general, basalts and andesites form the flank of the volcano, with rhyolites and small volumes of dacites occurring at the summit (Donnelly-Nolan, 2008).

Mineral Compositions: Despite a number of detailed petrological studies, there is a notable paucity of published mineral data, with most papers only publishing representative analyses:

- Gerlach and Grove (1982) report N=8 Cpx from a variety of units (Modoc basaltic-andesite, older and later platy olivine andesite, Medicine Lake Dacite, Glass Mountain Rhyolite).
- Grove and Donnelly-Nolan (1986) report N=4 Cpx and N=3 Amp from three types of magmatic inclusions from Pleistocene-Holocene silicic flows.
- Grove et al. (1997) present data from N=1 Cpx and N=3 Amp from Glass Mountain
- Grove et al. (1988) report N=4 Cpx analyses from the Burnt Lava flow
- Kinzler (1985) and Kinzler et al. (2000) report the composition of a N=5 and N=1 Cpx from the Callahan lavas respectively.

We obtain N=21 Cpx and N=6 Amp after filtering for quality. Cpx return a median pressure of 0.8 kbar using W2021, and 1.7 kbar using J2022, and Amp return a median pressure of ~2.5 kbar.

Melt Inclusions: Sisson and Layne (1993) measure a H_2O content of ~0.2 wt% from Black Crater MIs using SIMS. Kinzler et al. (2000) report an Amp-bearing MI within an Mg-rich olivine with ~3 wt% H_2O. No CO_2 data exists for either the melt phase or the bubble in these studies. Thus, we do not calculate saturation pressures for these inclusions. MI work analysing the melt and vapour phase for H_2O and CO_2 in the Paint Pot basaltic deposit is currently in progress (see Couperthwaite et al., 2022). To our knowledge, there has been no melt inclusion work performed on the more silicic compositions at Medicine Lake. This may reflect the paucity of rapidly-quenched tephra at this volcano dominated by lava flows; only two ash falls are documented from the Holocene (Heiken, 1978).

Experimental phase equilibrium: Grove et al. (1982) conducted experiments investigating the origin of the calc-alkaline series at Medicine Lake. However, other than demonstrating that P_{H2O} must be greater than 1 kbar to generate calc-alkaline compositions, no further constraints are placed on magma storage depths. Wagner et al. (1995) performed experiments on the Late Pleistocene Lake Basalt, reproducing lava compositions and phenocrysts in 1 kbar H_2O-saturated experiments. However, they do not perform experiments at different pressures, so the same relationships may be have reproduced at other pressures (e.g. 0.5, 2 kbar). Grove et al. (1997) perform experiments at 1, 1.5, and 2 kbar to investigate the origin of the Rhyolite of Glass Mountain. They suggest that the presence of Amp in more mafic inclusions indicates crystallization at >2 kbar, while Ol-Plag and Ol-Plag-Cpx inclusions indicate crystallization at near H_2O-saturated conditions at ≤1 kbar. Finally, Bartels et al. (1991) perform experiments at 1 atm, 10 and 15 kbar on high-aluminium basalts from Medicine Lake, demonstrating that these liquid compositions are close to equilibrium with a mantle lherzolite source. However, the high-pressure nature of these experiments mean they do not provide insights into the depth at which magma is stored in the crust beneath Medicine Lake.

Geophysics: Evans and Zucca (1988) and Chiarabba et al. (1995) use active source seismic topography (the NeHT experiment of 1985) and seismic refraction studies conducted in 1982 and 1984 to image P-wave velocity and attenuation beneath Medicine Lake. Evans and Zucca (1988) obtain ~1–2 km depth resolution in the upper 5–7 km of the crust, and image a low Q (high attenuation), low velocity region in their layer 3 beneath the east central caldera with a volume of a few 10s of km^3 (1.2–3.25 km depth bsl, 3.6–5.6 km below ground level). Chiarabba et al. (1995) experiment with alternative inversion strategies and find that the low-velocity body is well resolved at 3–5 km depth (bgl), although some less-stable inversion strategies suggest that the low velocity zone is deeper (>6.8 km). Overall, Chiarabba et al. (1995) conclude that the low velocity zone likely occurs at 3–4 km depth (bgl), but could exist as deep as 7 km depth. The small size of the low velocity anomaly identified in these two seismic studies, roughly 10 km wide horizontally, can account for the fact it is not seen in teleseismic studies (e.g., Ritter and Evans, 1997).

Pitt et al. (2002) report 1 LP EQ beneath Medicine Lake in Dec 1989 (15 km basl). The notable paucity of seismometers (particularly three component broadband) means that there have not been any more recent investigations of magma storage using passive source techniques since the flurry of geothermal exploration in the 1980s (Fig. 4g).

Interpreting geodetic data is complicated by the fact that Medicine Lake impinges on the western edge of the Basin and Range, meaning it is subject to regional extension. Additionally, Medicine Lake's large volume, and therefore mass, means that it loads and deforms the surrounding crust. These "background" signals make it difficult to distinguish the smaller signals resulting from inflation and deflation of crustal magma chambers (Dzurisin et al., 1991; Poland et al., 2006). Dzurisin et al. (1991) and Dzurisin et al. (2002) examined levelling surveys from 1954–1989, a small summit survey from 1988, and seismicity occurring 1978, 1981, and 1988. They infer that regional/loading signals overwhelm the minor amount of signal which may arise from crystallization and magma withdrawal.

Poland et al. (2006) investigated campaign GPS data and InSAR data from Medicine Lake Volcano. InSAR identifies ~10 mm/yr of approximately radially symmetric subsidence centred on the caldera region (consistent with GPS and levelling data). They show that the GPS horizontal displacements are inconsistent with the model of Dzurisin et al. (2002) of volume being lost at 10–11 km depth, because this should produce radially-inward horizontal deformation up to 40 km radius. Instead, they invert for a Mogi point source at shallower depths (~6 km) to explain the fact only GPS stations within ~10 km of the summit show inward deformation. This deformation source can also be fitted as a deflating sill at 5 km depth. However, this sill fit has a higher misfit, and doesn't effectively recreate the vertical deformation of the 1954–1989 levelling survey of Dzurisin et al. (1991). Overall, Poland et al. (2006) suggested the dominant signal is edifice loading and extension of a hot weak crust, rather than magma withdrawal. Similarly, Parker et al. (2014) examined additional InSAR data (up to 2011), suggesting that deformation is caused by tectonic extension and gravitational loading, with a possible role for cooling and crystallization of an intrusive body at depth (rather than an active magma chamber). Given that geodetic signals appear not to represent magmatic processes at Medicine lake, we do not include them on Fig. 4.

Other: Another possible constraint on magma storage depth comes from geothermal exploration drilling, which encountered hydrothermally-altered granitoid rocks at 2–2.9 km depth below the summit caldera (Zircon dates of ~332 ka, Donnelly-Nolan et al., 2008; Lowenstern, 2003). While down dropping of the caldera and erosion over 100s of kyrs can alter the current depth vs the emplacement depth, down dropping is thought to have been limited to ~240–440 m, and erosion is relatively negligible in the high desert (Donnelly-Nolan et al., 2008, Donnelly-Nolan written communications).

Summary and future directions: We suggest that the most precise constraints on magma storage beneath Medicine Lake could be obtained by performing detailed MI studies on rapidly quenched material where available. For slower-cooled lava flows, detailed analysis of minerals and any fresh glasses could help provide barometric constraints to supplement the small amounts of publicly-available mineral data. Without densification of the seismic network with three component broadband seismometers, or targeted local studies, additional geophysical constraints are unlikely to be obtained in the near future.

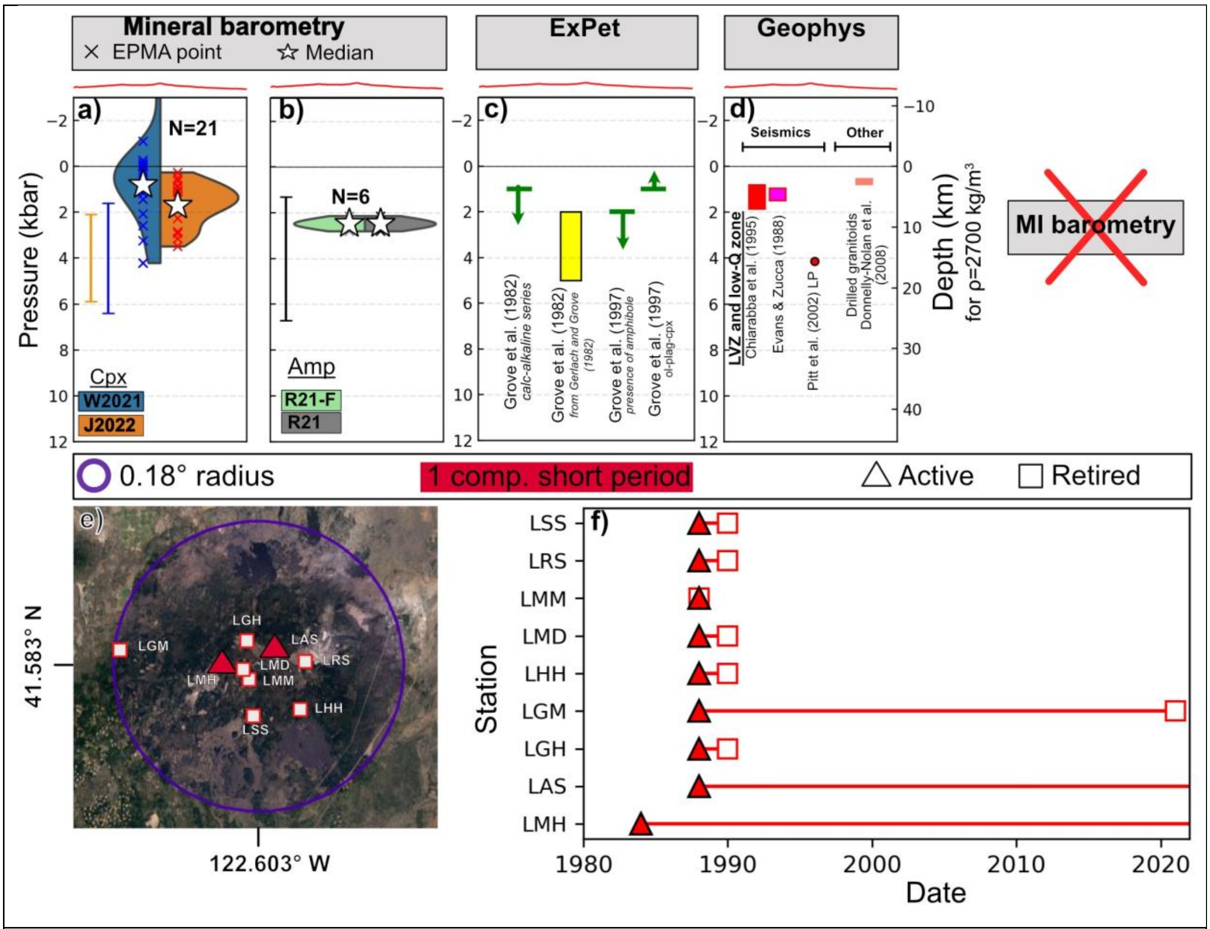


Fig. 4 – **Compilation of magma storage depths at Medicine Lake Volcano (a-d) and summary of the seismic network (e-f).** Summary of barometric constraints at Medicine Lake Volcano. The

red profile shows the height above sea level across an N-S section spanning 30 km transecting the summit

Crater Lake/ Mount Mazama

The climatic eruption of Mount Mazama at ~7.7 ka produced the modern-day caldera known as Crater Lake. Activity at Mount Mazama began around ~420 ka, producing basaltic andesite, medium-K andesites and dacites. The first preclimactic rhyodacites erupted at ~27 ka, and the evolution of this silicic reservoir was terminated by the massive climatic eruption of ~50 km^3 at 7.7 ka (Bacon and Lanphere, 2006). Post-caldera volcanism was dominated by andesite for 200–500 yrs after the climatic event, followed by an eruption of a rhyodacite at 4.8 kyrs. There are also 20 cinder cones within Crater Lake National Park (Prueher and McBirney, 1988).

Mineral Compositions: We compile the following mineral data:

- N=16 Cpx from preclimatic rhyodacites from Nakada et al. (1994)
- N=126 Cpx analyses from the 8 dacitic-rhyodacitic deposits spanning 71–7.7 ka described in Wright et al. (2012, kindly provided by the authors).
- N=194 Cpx and N=245 Amp from the original handwritten datasheets of EPMA analyses for the climatic samples described in Druitt and Bacon (1989).

The dacitic-rhyodacitic deposits at Crater Lake are outside the calibration range of the W2021 barometer, which could explain why calculated pressures are so shallow (median=-0.2 kbar). The median pressure for the J2022 barometer is ~1.2 kbar, with a skewed distribution to higher pressures (this barometer does not return very shallow pressures). Si-Al filtered Amp pressures are very similar to those unfiltered, with median pressures of ~ 3 kbar. There is also a small cluster of Amp-only pressures at ~7 kbar, from samples 80c444 (Ol-Px rich scoria from top of the climatic ignimbrite), 82C882 (high-Sr scoria from top of climatic ignimbrite), 82C938 (high-Sr enclave from Llao rock) and 1290 (low-Sr scoria from the top of the climatic ignimbrite), all from Druitt and Bacon (1989). It is difficult to interpret the single Cpx measurement from Wright et al. (2012) yielding a pressures in a similar range to these high Mg# amphiboles without detailed information on the analytical uncertainty associated with these measurements (see Wieser et al. 2023a). Additional mineral analyses will be vital to pin down the possibility of a deeper region of more mafic magma storage.

Melt Inclusions: Bacon et al. (1992) analyse plagioclase-hosted MIs from three rhyodacitic Holocene eruptions (~7kyrs-6.8 yrs BP) from Crater Lake by FTIR (Llao Rock, Cleetwood, and the climatic event). CO_2 concentrations in these MIs are <25 ppm, and often undetectable by FTIR. We remove MIs with low H_2O contents (<3.1 wt%) which the authors suggest may have a connection to the outside, leaving N=10 MIs. Mandeville et al. (2009) analyse plagioclase and pyroxene-hosted MIs from the same three eruptive episodes as Bacon et al. (1992), also using FTIR. None of the reported N=48 MIs have visible connections to the outside or cracks, and CO_2 concentrations are below the FTIR detection limit. Wright et al. (2012) analyse N=127 plagioclase and pyroxene-hosted MIs from 8 dacitic-rhyodacitic deposits spanning 71–7.7 ka using SIMS (along with a subset by FTIR). They identify high H_2O (3–4.6 wt%) and low H_2O (<2.4 wt%) populations of MIs. They suggest that the low-H_2O population likely reflects leakage, and diffusive re-equilibration. Thus, for consistency with Bacon et al. (1992), we do not calculate saturation pressures for inclusions with <3.1 wt% H_2O. Wright et al. (2012) only detect CO_2 significantly above detection limit in deposits from the 71 ka Pumice Castle. All Crater Lake MI saturation pressures cluster at ~1 kbar depth. To our knowledge, no vapour bubbles have been measured in these more silicic MIs, although this doesn't mean they are CO_2-free.

Experimental Petrology: We are not aware of any published experimental petrology studies placing constraints on magma storage depths beneath Crater Lake.

Geophysics: The only seismic constraints at Crater Lake that we are aware of is a single LP at ~32 km depth (Nichols et al., 2011), and a brief mention of a low velocity zone in the lower crust below Crater Lake in the regional teleseismic study by Harris et al. (1991). However, Harris et al. (1991) do not provide a depth or place any quantitative constraints on the size of this body, so we do not include this in our compilation. The lack of seismic constraints on magma storage is not surprising; the seismic network at Crater Lake was non-existent for more than 20 years in the late 1980s to mid 2000s (Fig.

5g), and has only been upgraded very recently with three component broadband seismometers. Once sufficient earthquakes have been measured on this new network, additional constraints on magma storage may be possible. Poland et al. (2017) summarize available geodetic constraints at Crater Lake, which show no deformation resolvable above survey noise since the 1980s.

Summary and Future work: We suggest that further petrological and experimental work examining the postclimactic materials erupted at Wizard Island could provide useful insights into the likely storage depths of the next eruption at Crater Lake. Examination of CO_2 within more silicic MI vapour bubbles would also be a worthy target, as would melt inclusion measurements on the numerous mafic cinder cones, which have been suggested to tap magma bypassing the centrals silicic reservoir (Prueher and McBirney, 1988). Although permitting would certainly be a challenge, a higher resolution array with active sources could help provide additional geophysical constraints.

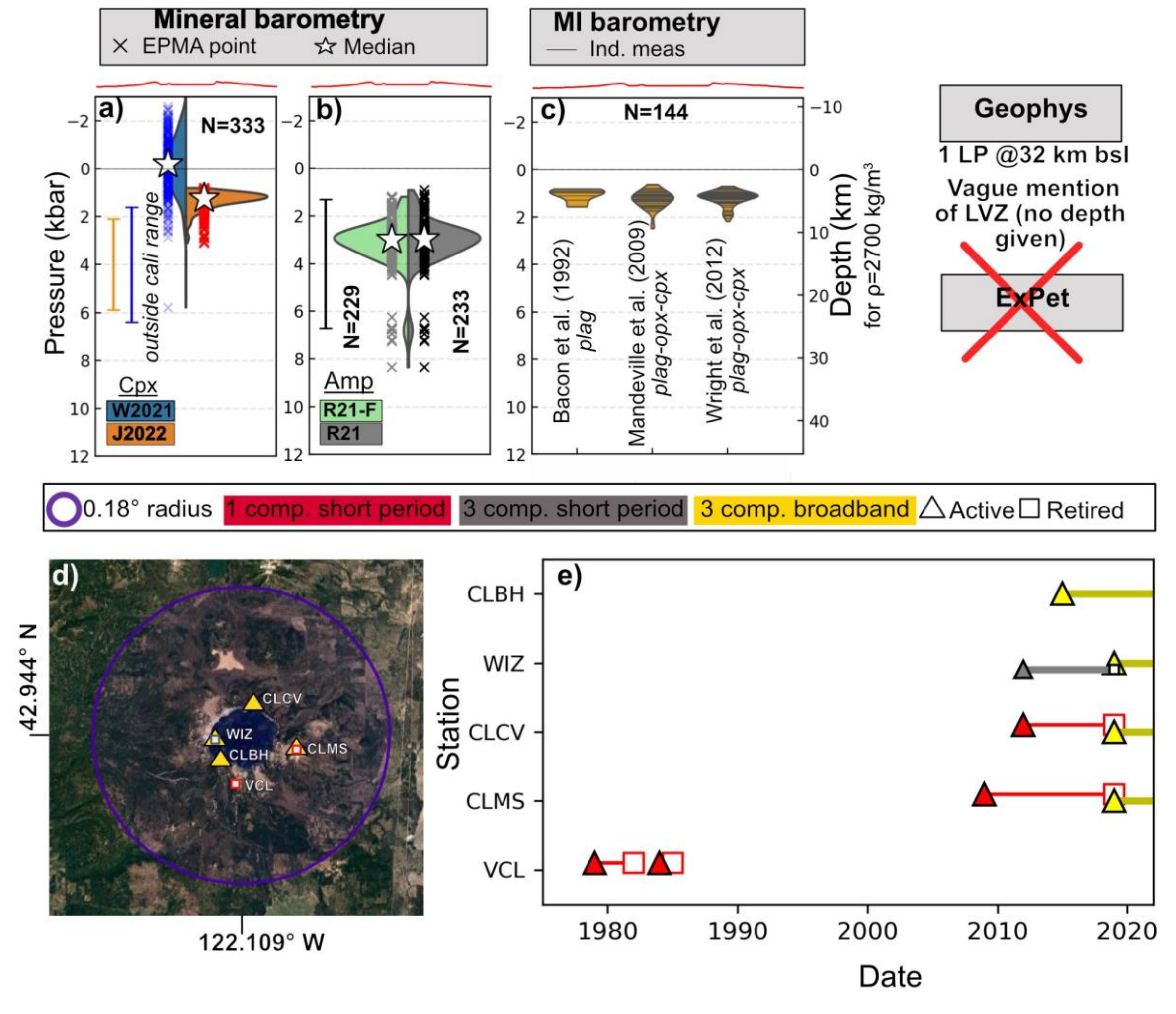


Figure 5 – **Compilation of magma storage depths at Crater Lake (a-c) and summary of the seismic network (d-e).** Summary of barometric constraints at Crater Lake Volcano. The red profile shows the height above sea level across a W-E section spanning 30 km transecting the summit

Three Sisters

The Three Sisters volcanic field consists of three prominent summits (North, Middle and South Sister), as well as a number of distributed vents. North Sister has a very monotonous basaltic-andesite composition, with activity between ~120–50 ka, including a small shield (Little Brother), and a string of fissures (Matthieu Lakes fissure, Fierstein et al., 2011; Schmidt and Grunder, 2011). Activity at Middle and South Sister has been largely contemporaneous, with Middle Sister erupting basalt-andesite and dacite, while South Sister erupts only intermediate to more felsic compositions. In general, relatively little petrological work has been done on this area.

Mineral Compositions: We were only able to compile N=6 Cpx from the Matthieu Lakes Fissure transecting North Sister from Schmidt and Grunder (2011), and N=11 Cpx from South Sister dacites from Waters et al. (2021). The small number of analyses make it harder to average out the effects of analytical uncertainty; the available data suggests storage centred around 1 kbar at North Sister and ~2 kbar at South Sister, although these differences are certainly within uncertainty of one another, and individual analyses show substantial overlap between the two centers.

Melt Inclusions: To our knowledge, there are no published MI analyses from South or Middle Sister. Mordensky and Wallace, (2018) analyse olivine-hosted MIs from North Sister using FTIR. 9/15 of these MIs had vapour bubbles. They find that minimal PEC has occurred (0–2.3%, representing ΔT=~20˚C). They perform a bubble correction similar to that of Aster et al. (2016), and infer ~48–78% of CO_2 is within the bubble. However, for such small amounts of PEC, where the vast majority of the bubble grows during syn-eruptive cooling, bubble reconstructions assuming re-equilibration between vapour bubble and melt can greatly overestimate bubble CO_2 contents (Wieser et al., 2021). Additionally, with such low amounts of PEC, the correction is heavily affected by the choice of FeO_t content, which shows scatter in local whole-rock compositions. Mordensky and Wallace (2018) report PEC-corrected major element data for N=8 North Sister MIs, six of which have CO_2 below-detection limit. Given the small number of analyses, low CO_2 contents in the glass, lack of published major element contents for many MIs, and lack of bubble CO_2 data, we do not perform saturation pressure calculations. Mercer and Johnston (2008) cite unpublished MI data from North Sister, which we were not able to obtain for this study.

Experimental Petrology: Mercer and Johnston (2008) perform experiments using a North Sister melt composition, mostly to constrain the lower crustal mineralogy the melt last equilibrated with. They propose based on phase relationships and the absence of garnet or amphibole signatures that mantle-derived melts likely stall at ~12 kbar in a deep crustal hot zone, and then ascent to ~1 km where observed phases such as Ol, Plag and Cpx crystallize. We do not include these depths in our compilation, as they are not precise constraints on magma storage locations, but instead constrain the likely ascent path based more on inference of crustal structure than precise experimental constraints on phase stability. While their experiments focus on Newberry Volcano, Mandler et al. (2014) draw comparisons with natural compositions erupted at the Three Sisters, indicating 'damp' not wet magmas are present at Three Sisters along the arc front, as well as in the rear-arc.

Geophysics: We are not aware of any seismic constraints on magma storage at Three Sisters, and the PNSN only locates 0–3 earthquakes within 10 km per year. Seismic constraints are not helped by the fact that there are relatively few seismometers within a very broad area, and these were only upgraded to broadband seismometers relatively recently (Fig. 6g).

The lightly vegetated flanks around Three Sisters makes it an attractive location for satellite-based geodetics (Poland et al., 2017). InSAR acquisitions between 1992–2000 reveal inflation over a broad area (10 x 20 km) centred ~6 km west of the South Sister summit (Wicks, 2002). InSAR was vital to identify this period of deformation, as it was offset to the west of the electro-optical distance meter (EDM) and tilt-levelling methods installed at the summit between 1985–1986. Wicks (2002) model this inflation with a Mogi point source at 6.5 ± 0.4 km depth (rlu), with a volume increase of 0.0023 ± 0.003 km^3. Dzurisin et al. (2006) supplement InSAR observations with tilt surveys from 1985, 1986 and 2001, EDM surveys from 1985–1986, Campaign GPS surveys from 2001–2002, and levelling in 2002–2003 along survey lines intersecting the deformation centre. They invert these four datasets, investigating Mogi point sources, elliptical and dislocation sources, finding that the best fit is a shallowly-dipping sill at 6.5 ± 2.5 km depth bgl. Dzurisin et al. (2009) further supplement this data with InSAR, GPS, and levelling data collected up to 2006. This new data reveals that the inflation rate has been decreasing exponentially. They suggest that the best fit shallowly-dipping sill proposed by Dzurisin et al. (2006) results from combining early InSAR data with later GPS data during this change in deformation, skewing the relative proportions of horizontal motion (which GPS is most sensitive to) and vertical deformation (which InSAR is most sensitive to). Dzurisin et al. (2009) instead propose a vertical prolate source geometry, which provide better fits to the data once these temporal changes are accounted for. This source sits at 4.4 km depth bgl with an aspect ratio of 0.9, which is the best fit if network translation is ignored (the source is 5.4 km bgl with an aspect ratio of 0.86 when accounting for network translation).

Riddick and Schmidt (2011) examine C-band InSAR from two satellites (ERS and ENVISAT), suggesting that deformation tails off following two separate linear trends (1998–2003, 2004–2010). Using a Mogi source, they obtain 5.5 km, 6.5 km using an ellipsoidal source, and 7 km using a sill source.

Wicks (2002) suggest that the deformation source could result from the injection of new magma, or pressurization of a hydrothermal system, with the former being more likely as hydrothermal activity is often accompanied with seismic activity (and this episode was relatively aseismic). Dzurisin et al. (2009) also conclude based on spring chemistry that an intrusion of magma is a more likely cause of deformation than a hydrothermal system perturbation.

Summary and Future work: Given recent renewed uplift ~5 km W of South Sister (Jan 2022) in addition to the deformation discussed above, more detailed petrological work on this edifice is warranted. In particular, MI constraints could help determine whether the depth inferred from geodetics is similar to that of magma reservoirs feeding past eruptive episodes. Unlike many Cascade volcanoes, South Sister has silicic tephra fall deposits suitable for such work (and, in fact local ash dispersion is one of the most probable future hazards in this area, Hildreth et al., 2012). In order to investigate the storage depths of the more mafic fissures and cinder cones of North Sister and the surrounding area, a detailed study of vapour bubble CO_2 in MIs is required. Experimental constraints could be used to investigate the relationship between mafic and silicic magmas, combined with new, high precision analyses of mineral compositions, to build a more coherent model of the magmatic plumbing system.

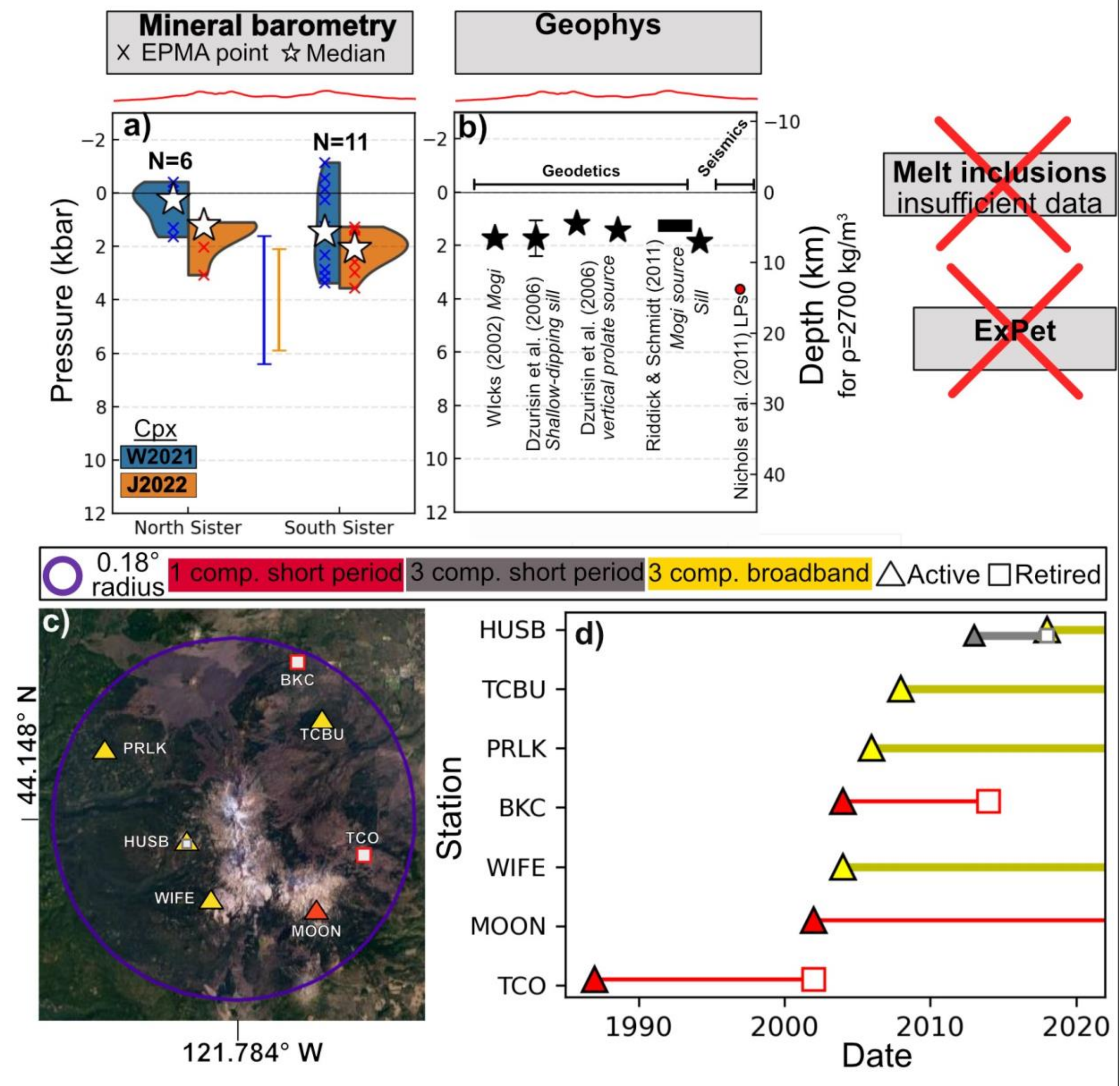


Figure 6 – **Compilation of magma storage depths at Three Sisters (a-b) and summary of the seismic network (c-d).** The red line shows the height above sea level across an approximately N-S section spanning 17 km transecting all 3 summits. c-d) Seismic stations vs. time.

Newberry Volcano

Newberry Volcano lies ~50–60 km east of the main arc front and covers the largest area of all Cascade volcanoes. It is second in volume only to Medicine Lake. Newberry exhibits predominantly bimodal volcanism; intracaldera eruptions are rhyolitic, while its north-westerly trending rift zone hosts basaltic-andesite fissures and cinder cones. Newberry caldera was formed at ~75 ka with the eruption of a compositionally-zoned basaltic-andesite to rhyolite tuff (Donnelly-Nolan et al., 2011).

Mineral Compositions/Melt inclusions: We were unable to find any published mineral compositions or MIs from Newberry Volcano.

Experimental Petrology: Mandler et al. (2014) perform 1 bar (anhydrous) and H_2O-saturated 1–2 kbar experiments on the ~75 ka caldera-forming tuff from Newberry Volcano. They find that the 1 kbar experiments best reproduce the samples from the caldera-forming tuff, but that these experiments were conducted with too high H_2O contents, because differentiation was likely H_2O-undersaturated. They state that it is difficult to constrain the pressure of storage in these undersaturated systems, where the effect of pressure on phase equilibria is small at crustal conditions. Overall, they conclude that differentiation occurred in the upper crust.

Geophysics: Extensive geophysical work has been performed at Newberry because of its geothermal potential. The teleseismic study of Stauber et al. (1988) indicated that no magma chamber is resolvable within the resolution of their study (e.g., ~5 km width). Using active source tomography with higher resolution, Achauer et al. (1988) identify a low velocity body at 3–5 km depth bgl, which they interpret to be a small silicic or stratified magma body, although the lower end of this body is difficult to resolve in their inversion. Zucca and Evans (1992) investigate P-wave attenuation using the same seismic data as Achauer et al. (1988). They find that the low velocity zone in their layer 3 has average attenuation, such that it may reflect a recently solidified, hot cracked pluton, rather than actual melt (which would have high attenuation). More recently, Beachly et al. (2012) use travel time tomography and forward modelling of arrival times and seismic amplitudes from an active-source seismic experiment with 75 three component seismometers in 2008. They identify a central low velocity anomaly at 3–6 km below the caldera floor. They find the best fit is a molten sill with a thin mush region at the bottom - in their schematic the melt body is located at ~4–5 km depth beneath the caldera.

The seismic network at Newberry was densified with six new three component broadbands in 2011 and two further upgrades to 3 component short period stations in 2019, increasing the opportunity for passive source techniques when supplemented by data from the active source campaigns. Heath et al. (2015) combine active and passive source seismic data collected on the 2008 array to better constrain seismic velocity, with increased resolution at depths >6 km (the limit of the Beachly et al. 2012 study). They identify the main low velocity volume at 3–5 km depth below the crater floor, with horizontal dimensions of 5 x 3 km, and a vertical thickness of 2 km. They suggest that the location of this body is consistent with it hosting the rhyolitic magmas erupted in the caldera. Their model requires ~10% melt with a minimum melt volume of 2.5 km^3 in this region. They also report LPs from PNSN seismometers between 2012 and 2015 at 7–11 km depth (rlu). Finally, Heath et al. (2018) use seismic autocorrelation, and find a coherent P-wave reflection at 2.5 km depth beneath the caldera, which they infer is generated at the top of the magma body.

Bowles-Martinez and Schultz (2020) use 3D magnetotellurics to identify a relatively resistive magma chamber beneath Newberry Volcano at 3–4 km depth below the crater floor. The relatively high resistivity of this body does not require melt and could be a fractured pluton. However, for consistency with the seismic studies described above, they show that this body could be melt, if that melt was relatively water-poor (~1.5 wt%). They indicate that such a low H_2O content is reasonable if the rhyolitic melt differentiated from a dryer basalt. However, mafic inclusions in the Big Obsidian Flow have a phase assemblage typical of relatively hydrous magmas (e.g. amphibole, two pyroxene and Fe-Ti oxides, Linneman and Myers, 1990). Additionally, melt inclusions indicate that differentiation of a basalt with ~0.3-0.6 wt% H_2O to a dacite at Kilauea Volcano raises H_2O contents to 2 wt% (Wieser et al., 2022c). Thus, it seems unlikely that fractional crystallization at ~3–5 km depth could produce such a dry rhyolite magma without a substantial contribution from melting of very anhydrous crustal material.

Dzurisin (1999) examine levelling data over a period of uplift between 1931–1994. They suggest that one possible mechanism for this uplift is the intrusion of 0.06 km^3 of magma ~10 km below the crater floor. It is hard to investigate this deformation source further, because no measurable volcanic deformation has occurred at Newberry since the 1980s (Poland et al. 2017).

Summary and Future work: Overall, Newberry Volcano has been subjective to extensive geophysical investigation. However, it is clear that substantially more petrological work involving mineral and MI compositions is required. In particular, MI work constraining pre-eruptive H_2O contents will help inform geophysical inversions (e.g., determining whether rhyolitic melts are as dry as suggested by Bowles-Martinez and Schultz, 2020). Additional experiments conducted using volatile contents inferred from melt inclusions could help constrain storage conditions further (Mandler et al., 2014).

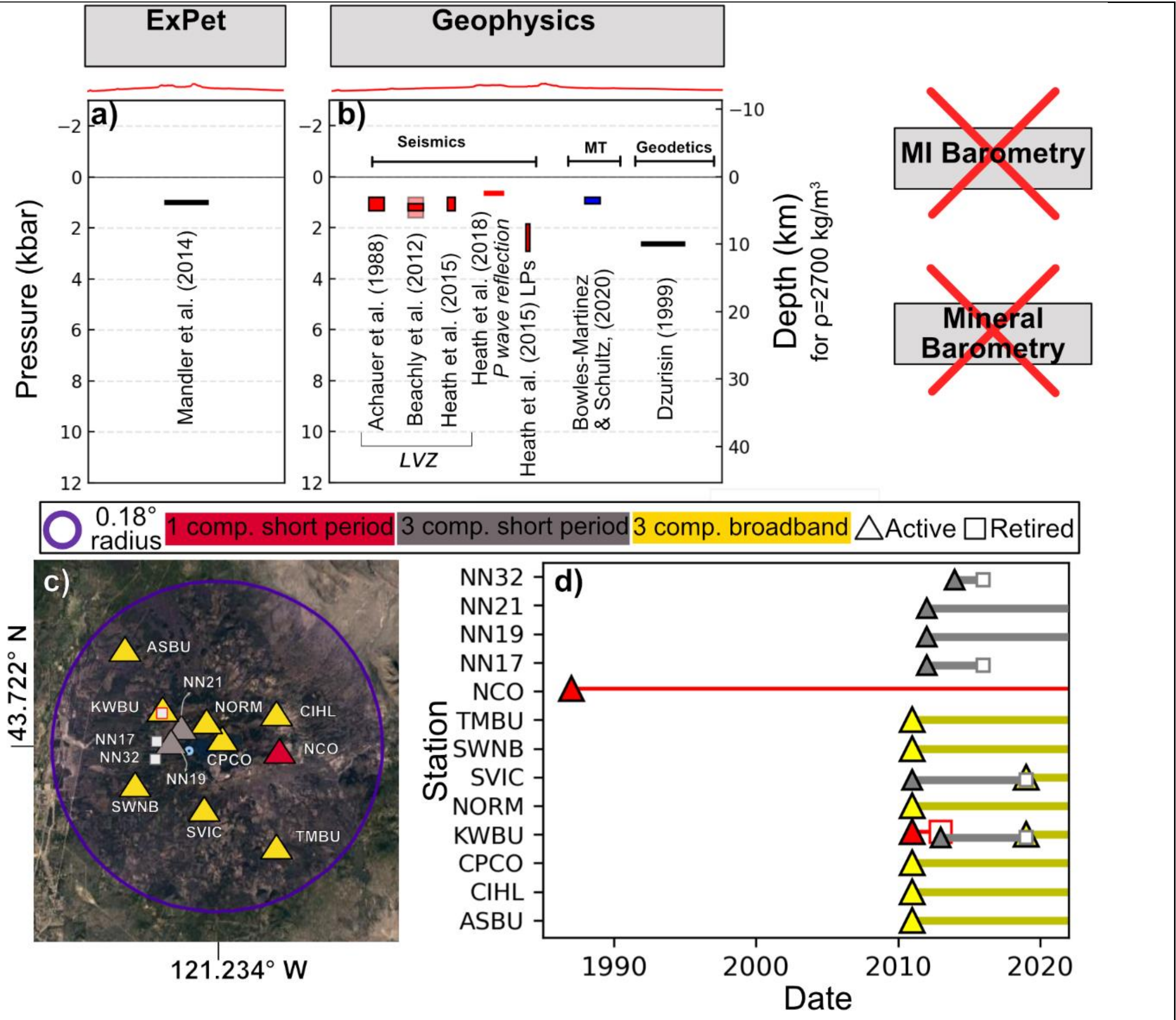


Figure 7 - **Compilation of magma storage depths at Newberry Volcano (a-b) and summary of the seismic network (c-d).** The red line shows the height above sea level across an approximately N-S section 55 km section transecting the crater. The unlabelled blue dot in c) is a strong motion station (HN).

Mount Jefferson

The area around Mount Jefferson has a complex volcanic history over 4–8 Myrs, with 160 separate units from monogenetic and composite cones, shields, and domes spread over 150 km^2 (Conrey, 1991). A transition from widespread mafic volcanism to more focused intermediate and silicic volcanism and the development of the modern edifice began at ~300 ka (Conrey, 1991, DiGuilio, 2015). Erupted rocks are characterized by very complex, heterogenous crystal cargoes (Conrey, 1991, Ustunisik et al., 2016).

Mineral Compositions: We obtain the following mineral analyses:

- N=87 Amp analyses from Conrey (1991) representing the last 200 kyrs of stratigraphy at Mt. Jefferson, from rhyodacites, dacites, and quenched mafic inclusions. While Conrey (1991) also present Cpx analyses, they do not report Na_2O data, so these measurements cannot be used with the J2022 and W2021 barometers.
- N=211 Amp, N=24 Cpx and N=25 Opx-Cpx pairs from various intermediate units from DiGuilio (2015). This units include the Whitewater Creek intermediate domes (32 ka), the Park Butte Andesite (154 ka), and the Pleistocene age basaltic andesite of Whiskey Creek. Only N=3 of these Opx-Cpx pairs are in high-T K_D equilibrium following Putirka (2008).
- N=32 Amp analyses from the ~10 ka Whitewater Creek andesite reported by Ustunisik et al. (2016).

The median Cpx-only pressure is ~2.5 kbar using W2021 and ~1.9 kbar using J2022. Amp-only median pressures (~3 kbar) are reasonably similar to these Cpx pressures. In contrast, median Cpx-Opx pressures are 6.7 kbar using Eq37–39 and 5.7 kbar using Eq36–39 from Putirka (2008). Given the relatively poor performance of Cpx-Opx barometers in arc magmas (Wieser et al., 2023c) and the relatively small number of Opx-Cpx analyses, we suggest that more substantial evidence is needed to infer a deeper magma storage zone.

Melt Inclusions: The only MI measurements from Mount Jefferson to our knowledge are from Ustunisik et al. (2016). However, they do not measure MI H_2O or CO_2, so no barometric constraints can be obtained from these samples.

Experimental Petrology: To our knowledge, there are no experimental constraints on magma storage at Mount Jefferson.

Geophysics: We are not aware of literature describing seismic or magnetotelluric investigations of magma storage. Given there is only a single one component short-period seismometer >10 km from the summit, and that the PNSN locates an average of 0 earthquakes per decade, the absence of seismic constraints on magma storage is unsurprising. No-ground based geodetic studies have been performed at Mount Jefferson. InSAR from the 1990s-2000s shows coherence, but no deformation (Poland et al., 2017).

Summary and Future work: Further petrological work would help to further investigate the plumbing system, particularly MI or experimental petrology. However, the low threat ranking of Jefferson, this work is perhaps not as urgent as similar data gaps at higher threat volcanoes (Fig. 1, Fig. 16).

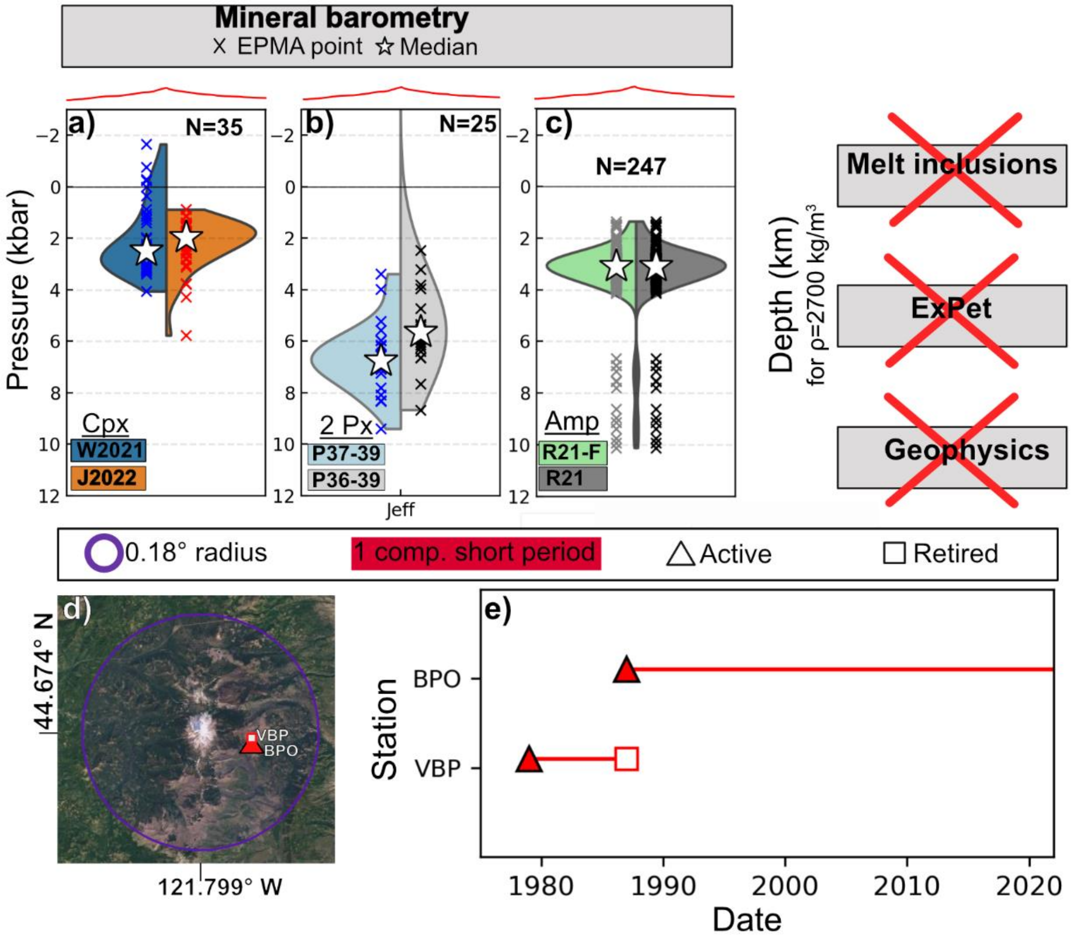


Figure 8 – **Compilation of magma storage depths at Mount Jefferson (a-c) and summary of the seismic network (d-e).** The red line shows the height above sea level across an approximately W-E section spanning 10 km transecting the summit.

Regional mid crustal anomalies around Mount Hood, Mount St. Helens, Mount Adams and Mount Rainier

To avoid repetition in the following sections, we discuss the regional anomalies in the mid to lower crust around Mount Hood, Mount St. Helens, Mount Adams and Mount Rainier here in a single section.

Stanley (1984) performed a regional magnetotelluric (MT) study, identifying a conductive zone in the region between Mount St. Helens, Mount Adam and Mount Rainier termed the Southern Washington Cascades Conductor (SWCC). He suggested that this feature reflects a band of conductive sediments and volcanic rocks of approximately Tertiary age. Hill et al. (2009) perform a higher-resolution MT study over a 35 km^2 area near Mount St. Helens, as well as a 2D line stretching from Mount St. Helens to just north of Mount Adams across the southern portion of the SWCC. They identify a conductor stretching beneath the summit of Mount St. Helens, merging with a thick conductive region at ~15 km depth, and stretching across to Mount Adams, where it has some weak upper crustal features. They interpret the shallow zone beneath Mount St. Helens as a magma conduit supplying the volcano, which was showing unrest during the survey. By extension, they suggest that the connected mid crustal feature also represents 2–12% interconnected melt, supplying the dacitic magmas erupted at Mount St. Helens and Mount Adams. Bedrosian et al. (2018) further investigate this region, and specifically whether anomalies result from magma or sediments, using new high density MT data from an array spanning the entire SWCC. They note that the conductor beneath MSH imaged by Hill et al. (2009) extends 10s of km away from the volcano, extending into a metasedimentary belt. They believe the conductivity of dacite partial melt would be dwarfed by the ~10x higher conductivity of these metasediments, and as a result conclude MT techniques alone cannot unambiguously distinguish between regions of magma storage vs. sedimentary deposits.

Flinders and Shen (2017) use 3D ambient-noise tomography to investigate the velocity structure of the SWCC, with a particular focus around Mount Rainier. They find a large low velocity zone in approximately the same region as the MT-defined SWCC, with its top at depths of ~10 km bsl towards the northern extent closer to Mount Rainier, and ~15 km depth closer to Mount St. Helens and Mount Adams. They suggest that the base is likely unconstrained in the model but may extend to ~27 km bsl. They also suggest that portions of the SWCC have seismic velocities most consistent with the presence of ~6% melt, particularly in the context of the large number of Quaternary volcanic vents over this feature (>100).

In addition to local anomalies at Mount St. Helens, Ulberg et al. (2020) identify a broad region with low P-wave velocity at >10 km depth around Mount Rainier to Mount Adams. They speculate that this may indicate fluid or melt present, or high crustal temperatures.

Jiang et al. (2023) use ambient noise interferometry on a regional seismic network to further investigate the origin of these crustal anomalies. Crucially, their approach uses data from the EarthScope array in addition to regional seismic networks, which helps to mitigate edge effects allowing them to expand their reconstruction to cover the area around Mount Hood. They identify two subparallel low Vs zones at 15–30 km depth bsl. One zone stretches from Mount Rainier to Mount Adams, and the other from Mount St. Helens to Mt Hood They intepret these anomalies as deep crustal magma sills with ~2.5–6% melt.

Mount Hood

Construction of the modern edifice at Mount Hood began at ~500 ka. Activity has since been dominated by remarkably homogenous andesitic (and sometimes dacitic) lava flows and domes, with no evidence for explosive eruptions in the regional tephra record (Scott and Gardner, 2017). The three most recent eruptive episodes are Polallie (13–20 kyrs), Timberline (1.5 kyrs), and Old Maid (~200 yrs, Koleszar et al., 2012), with the Main Stage preceding this (>29 kyrs, Scott et al., 1997). We also discuss analyses from the Parkdale flow (7.5–7.7 kyrs, Scott et al., 1997) and the Main Stage Cloud Cap lavas which erupted from satellite vents between ~400–600 kyr (Keith et al., 1985).

Mineral Compositions: We obtain the following mineral compositions:

- N=15 Cpx analyses from the Main Stage and Parkdale Flow from Darr (2006).
- N=123 Cpx analyses from the Main Stage Cloud Cap, Main Stage, and Polallie from Cribb (1997)

- N=109 Amp compositions from Koleszar (2011), Koleszar et al. (2012) and Loewen (2012) from the Old Maid, Timberline and Polallie eruptive episodes.

The median Cpx-only pressure is ~1.4 kbar for W2021, and ~1.6 kbar for J2022, with W2021 extending as a tail to much shallower pressures (while J2022 shows the absence of very shallow pressures typical of this barometer). The median Amp-only pressure is ~1.6 kbar regardless of filters, which is remarkably similar to the Cpx-only pressure estimates.

Melt Inclusions: Koleszar et al. (2012) present Plag, Opx, and Cpx hosted MIs (N=38) from the Old Maid, Timberline, and Polallie Stages. A subset of MIs that were large enough for double polishing (N=12) were measured using FTIR and yielded no CO_2 above the detection limit. The remaining MIs (<60–80 µm diameter, N=28) were measured by SIMS. These inclusions contain CO_2 contents up to 2400 ppm, although they note that the lack of standards with >540 ppm CO_2 required their calibration line to be extrapolated for these measurements. These high CO_2 contents are unusual in such evolved materials, so Koleszar et al. (2012) suggest they may result from the presence of undetected microcracks with CO_2 contamination during sample preparation. They also note that many MIs contain vapour bubbles, which may contain additional CO_2. Their FTIR H_2O measurements range from 0.8–3.6 wt%, while SIMS measurements range from 0.9–5.4 wt%. The higher SIMS H_2O contents may reflect the superior ability of smaller MIs to retain high volatile contents (e.g., less resistant to cracking/rupturing), although it is possible this disagreement also reflects calibration issues. They note that there is a general trend towards lower H_2O contents with increasing SiO_2, indicating MI entrapment during degassing induced-crystallization, which makes it hard to apply a filter based on H_2O contents. Thus, considering the poorly-constrained nature of CO_2, and the probable influence of degassing on H_2O, saturation pressure from these MIs are not a rigorous constraint on magma storage.

Experimental Petrology: While Mount Hood andesite has been used widely as an experimental starting material, we are not aware of any experimental studies directly relating to magma storage conditions beneath Mount Hood. Additionally, erupted Mt Hood andesites are mixed magmas and are thus not representative of a single multiply-saturated liquid (Kent et al., 2010).

Geophysics: Weaver et al. (1982) report the results from a 16–station seismic network established in 1977 at Mount Hood. They find no significant velocity anomalies beneath Mount Hood indicative of magma reservoirs. Use of earthquakes directly, rather than through inversions for crustal structure, has been hindered at Mount Hood by the fact that low frequency earthquakes and tremor are exceedingly rare. Jones and Malone (2005) summarize that most earthquakes detected on the Mount Hood seismic network have characteristics of tectonic earthquakes, likely reflecting the northern edge of regional Basin and Range seismicity. Following a M4.5 earthquake in June 2002 located ~4.6 km south of Mount Hood, there was a swarm of >200 aftershocks, which Jones and Malone (2005) subdivide into four groups. A small subset of these earthquakes (Group D) occurred at very shallow depths. Jones and Malone (2005) suggest that these earthquakes may reflect volcanic processes beneath Mount Hood, although they do not speculate further as to whether these represent magma or fluid movement. Other than the regional mid-crustal anomalies discussed above, there are no further seismic constraints on upper crustal storage to our knowledge. In part, this reflects the fact that no local high-resolution study has been conducted using modern instrumentation. Poland et al. (2017) summarize available geodetic constraints at Mount Hood, which show no consistent deformation patterns that can be associated with volcanic activity since the 1980s.

Summary and Future work: Future work remeasuring CO_2 and H_2O in MIs and their vapour bubbles using more robust SIMS or FTIR calibrations would help resolve whether the high-pressure MIs of Koleszar et al. (2012) represent a deeper magma storage region or an analytical artefact. Hints of higher-pressure storage (2–4 kbar) are perhaps seen in the Cpx and Amp pressures; coupled measurements of mineral chemistry and MIs within a single crystal would help to investigate this further. Like many of the volcanoes discussed so far, Mount Hood's seismic network has been recently densified with three-component broadband seismometers (Fig. 9e). Once sufficient earthquakes have been recorded on this network, local, passive-source inversions should provide additional constraints on the presence/absence of magma storage regions and low velocity zones, and a greater understanding of the origin of earthquakes at Mount Hood (Jones and Malone, 2005).

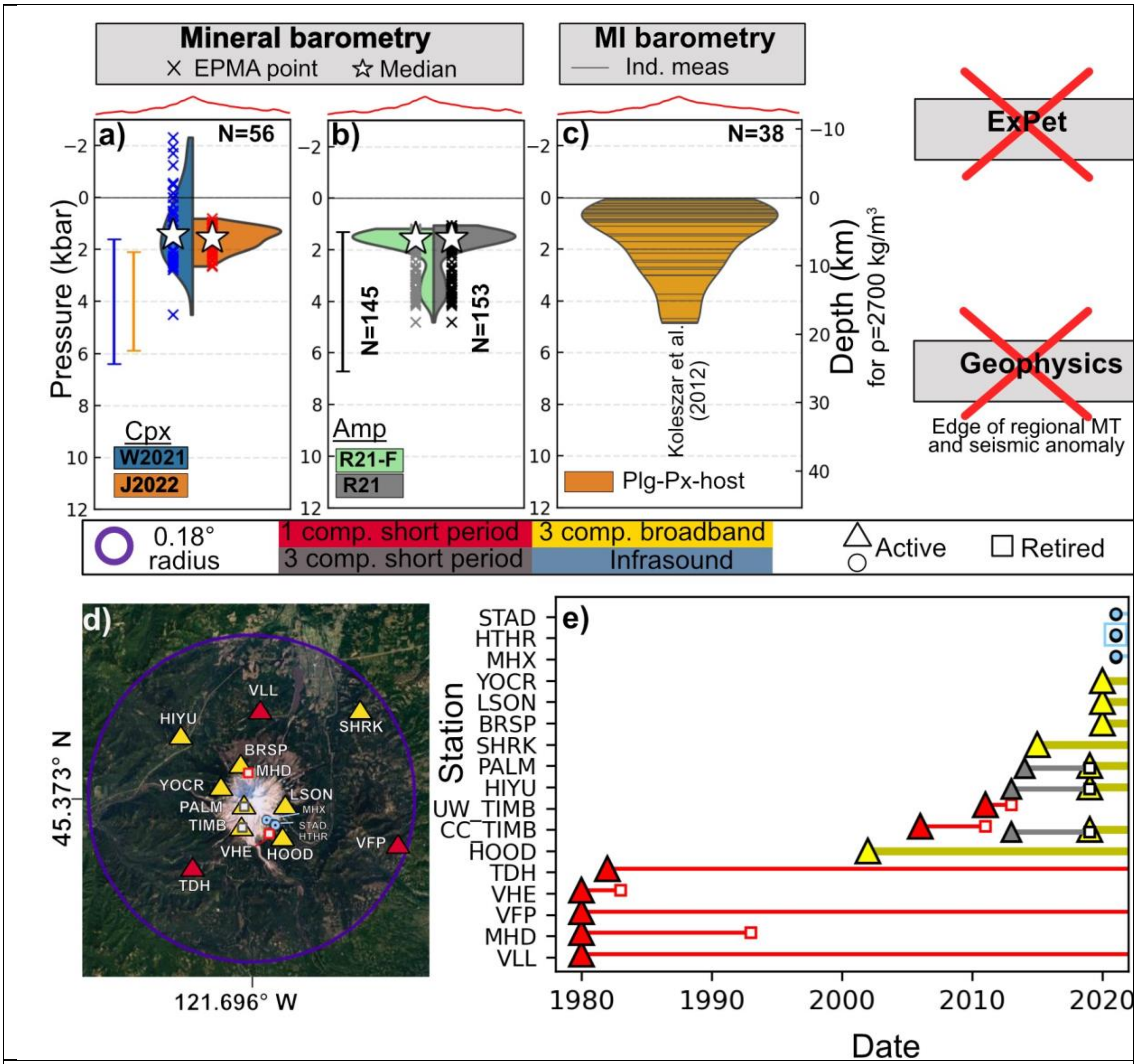


Figure 9 – **Compilation of magma storage depths at Mount Hood (a-c) and summary of the seismic network (d-e).** The red line shows the height above sea level across an approximately W-E section spanning 20 km transecting the summit. Blue dots on map are infrasound stations.

Mount St. Helens

Mount St. Helens is located 53 km west of Mount Adams and 35–50 km W of the main arc front, so can be classified as a fore-arc volcano. It erupts primarily dacitic bulk compositions with plagioclase, pyroxene and amphibole phenocrysts (Hildreth, 2007), although erupted products range from basaltic to rhyodacite. Many display evidence of the mingling of basaltic and a dacitic magma (Pallister et al., 2017). It is one of the youngest and most active volcanoes in the Cascades, erupting more than half its 75 km^3 magma volume in the last 28 kyrs, and exhibiting five major explosive eruptions in the last 500 yrs. This high activity relative to other Cascade centers has been attributed to its location within a small pull-apart basin (Pallister et al., 2017). Following its Plinian eruption in 1980 and re-awakening in 2004–2008, it represents one of the best-studied Cascade volcanoes both in terms of petrology and geophysics (Fig. 10).

Mineral Compositions: We compile the following mineral data:

- N=57 Cpx compositions from the Kalama (~1480 AD) and Castle Creek andesites (1.9–1.7 kyr BP) from Cooper and Reid (2003).

- N=21 Cpx from the 2004–2005 eruption from Rowe et al. (2008).
- N=4 Cpx from the Castle Creek andesite from Smith and Leeman (1993). N=49 from the 2004–2005 episode obtained from the Rowe et al. (2008) USGS data repository, and an additional N=77 analyses from Humphreys et al. (2019) attributed to Rowe et al. (2008).
- N=171 from the May 1980 cryptodome and pumice fall, the June-12th 1980 airfall, and the July 1980 pyroclastic flow from Humphreys et al. (2019).
- N=171 from the 1980 AD eruption from Loewen (2012).
- N=446 from samples spanning 1980–2004 AD from Thornber et al. (2008).
- N=54 from mafic Castle Creek samples from Wanke et al. (2019).

The median Cpx-only pressure is 2.3 kbar using W2021, and 1.8 kbar using J2022, with relatively similar distributions (although W2021 shows a deeper tail). Filtered and unfiltered Amp-only pressures are 3.1 and 3.2 kbar respectively, although, as for Cpx, the distributions are quite broad. In general, Amp pressures are offset~ 1 kbar deeper than Cpx, which is well within the uncertainty of these methods.

Melt Inclusions: Rutherford et al. (1985) measure 57 plag-hosted MIs from the May-18 pumice using EPMA, calculating H_2O using volatiles-by difference techniques (~4.6 wt%). Blundy and Cashman (2005) measure H_2O using SIMS in mostly Plag-hosted MIs (some Amp- and Opx-hosted) from blast deposits, pyroclastic flows and domes from May-Oct, 1980. Texturally, many of these MIs show evidence for connection to the outside of the crystal, and there is a correlation between H_2O and SiO_2. These textural and chemical trends indicate decompression-induced degassing accompanying MI entrapment, meaning that MIs saturation pressures may be weighted towards recording processes occurring during magma ascent. Blundy and Cashman (2005) state that their preliminary FTIR measurements indicate that CO_2 contents are very low, so pressures can be determined using H_2O-only saturation pressures. However, Blundy et al. (2010) supplement the 2005 analyses with new SIMS analyses of CO_2 in N=77 MIs from 9 eruptive episodes between 1970–1984, finding CO_2 above the FTIR detection limit. We only use these later measurements. This is intriguingly similar to the scenario at Mount Hood where Koleszar et al. (2012) find no CO_2 using FTIR, but abundant CO_2 using SIMS. The SIMS analyses of Blundy et al. (2010) for MIs from the 1980 plinian episode have relatively low CO_2 (<400 ppm) and high H_2O (~4–6 wt%), while the later subplinian to vulcanian and effusive events have higher CO_2 and lower H_2O. They attribute these differences to CO_2-flushing as the eruption progressed. Four MIs have 0.4–1.7 wt% CO_2, which Blundy et al. (2010) link to much deeper magma storage.

Experimental phase equilibrium: Rutherford et al. (1985) perform experiments on a bulk sample of MSH dacitic pumice at 1–3.2 kbar, varying the fluid composition and oxygen fugacity. They show that the observed phase assemblage and crystallinity of the May 18th 1980 magma can only be produced if $P_{H2O} \neq P_{Total}$, requiring either H_2O-undersaturation, or a relatively CO_2-rich melt. They conclude that the upper part of the MSH magma reservoir was at a pressure of 2.2 ± 0.3 kbar, P_{H2O} was 50–70% of P_{total}, and T was 930 ± 10˚C. However, they note that the exact storage pressure is not constrained because these conditions were not simultaneously satisfied in different experiments. Rutherford and Devine (1988) perform additional experiments at 920˚C and 2.2 and 3.2 kbar, with variable fo_2 and X_{H2O} to further investigate Amp stability. They find that the phase assemblage of the 1980 eruption including Amp is reproduced at P=2.2 kbar, T=920 ˚C, and $X_{H2O} \geq 0.67$, with a surge of Plag crystallization occurring when X_{H2O} decreased just before eruption.

Gardner et al. (1995) perform experiments at 1, 1.5, 2.5 and 3.5 kbar and 850°C to determine storage pressures and water fugacity of 6 dacitic magmas from the last 4000 yrs. For different dacite units, they invoke storage depths between ~3.5–1.5 kbar. Their results suggest that 4000–3000 yrs ago, dacites were H_2O-saturated (5.5–6.5 wt%), while more recently-erupted dacites were H_2O-undersaturated (<5 wt% H_2O). They suggest this shift represents increasing mafic input, which dilutes H_2O and adds CO_2 (and also explains the appearance of andesitic bulk compositions). Constraints on magma storage are also provided by the stability of the mineral cummingtonite (a type of amphibole), which breaks down to orthopyroxene (Geschwind and Rutherford, 1992), indicating similar storage conditions to Gardner et al. (1995).

Rutherford and Devine, (2008) perform experiments on the 2004–2006 dacite, suggesting that the Fe and Al-rich Amp cores formed at 2–3 kbar, and 900˚C, as Amp forming in experiments at <2 kbar had lower Al than observed products. They suggest the observed An_{68-40} Plag compositions form when pressure drops to 2 kbar at 900˚C, and the outer rims of some Amp phenocrysts may have formed at 1–2 kbar.

Geophysics: Scandone and Malone (1985) use subsidence recorded by electronic tiltmeters in June-November 1980 to make a first estimate of the reservoir depth supplying the 1980 eruption (~7–9 km, rlu). They also analyse earthquake hypocenters accompanying each explosive event, identifying an aseismic zone at ~ 7 km depth (rlu) extending vertically for 6+ km which they suggest is a magma reservoir connected to the surface by a ~50 m wide conduit. Barker and Malone (1991) use earthquake focal mechanisms to identify an aseismic zone at 7–11 km bsl associated with magma storage. Musumeci et al. (2002) relocate 447 earthquakes from the late 90s to produce a 1D velocity structure beneath Mount Saint Helens, and identify a magma reservoir at ~5.5–10 km depth (bsl), and a thin vertical conduit similar to that invoked by Scandone and Malone (1985)**.** More recently, Waite and Moran, (2009) present a P-wave travel time velocity model using earthquake data recorded on the local network over 25 yrs, supplemented by 19 temporary broadband seismometers from 2005–2006. They identify a low-velocity zone at ~2–3.5 km bsl which they attribute to a shallow magma storage zone. Their model has limited resolution beneath 6 km, but they identify low velocities at ~5.5–8 km bsl in an aseismic zone, which approximately aligns with the older estimates described above.

The numerous geophysical studies described above mostly imaged the upper crust, as travel time tomography struggles to produce high resolution images at >6 km depth. Kiser et al. (2016) present results from the active source portion of the iMUSH (imaging Magma Under St. Helens) project. They identify a high V_p/V_s anomaly at 4–13 km bsl which they attribute to magma storage, and a low Vp column extending from 15 km to the Moho to the southeast of Mount St. Helens. Kiser et al. (2018) build on this study, using a finite-frequency tomographic method to place more detailed constraints on the geometry of the magma storage region. They identify a number of low Vp anomalies forming a near continuous body spanning 3.5–14 km bsl, with the highest amplitude Vp anomalies at 4–6 km bsl (interpreted to represent 10–12% melt, dropping to ~8% at 7km depth, and continuing to decrease downwards).

Ulberg et al. (2020) use local source V_s and V_p tomography as part of the iMUSH broadband array of 70 broadband seismometers to image the upper 20 km of the crust beneath Mount St. Helens. They identify a low P- and S-wave anomaly at 6–15 km depth bsl, with a diameter of 5–7 km, which they interpret to represent a magma storage region with ~3% partial melt over ~15–20 km^3. They also image the broader low P-wave velocity region discussed above in the section '*Regional mid crustal anomalies…*'. Ambient noise imaging from the same array showed low-velocity lower-crustal anomalies between Mount St. Helens and Mount Adams (Crosbie et al., 2019).

Interestingly, neither Kiser et al. (2016, 2018), Ulberg et al. (2020)**,** nor Crosbie et al. (2019) image the low velocity region at 2–3 km bsl identified by Waite and Moran (2009). Ulberg et al. (2020) suggest that the difference between the inversion techniques in the two studies may explain this discrepancy, while Kiser et al. (2018) suggest that the low velocity zone may have been a temporary anomaly related to dome-forming activity between 2004–2008. Alternatively, the magma body may be too small to be resolved at the relatively long wavelengths of microseismic noise used in ambient noise imaging (Crosbie et al., 2019).

Lisowski et al. (2008) examine GPS deformation associated with the onset of unrest in 2004. They model the deformation in an elastic half space model as arising from a vertically-elongate magma reservoir centred at ~7–8 km (basl). Mastin et al. (2008) model geodetic data from 8 continuous GPS stations as an ellipsoidal source with its top at 5±1 km (basl), and the center offset 1.3–1.6 km east of the crater centre. The base of this source is less well constrained; they place it somewhere below 10 km (likely 10–20 km basl).

Anderson and Segall (2013) invert geodetic data from the 2004–2008 period, along with information on extruded lava dome geometry. Using a range of input parameters (e.g. melt H_2O), they show a probabilistic estimate of magma chamber geometry from 100 randomly sampled outputs from their

Markov-Chain Monte Carlo simulations. They estimate that the centroid of the magma chamber is ~11–18 km below the crater floor, with an aspect ratio of at least 2 (e.g. vertically elongated). On Fig. 10, we show the extent of the magma chamber indicated on their Fig. 11 within the 67% contour line of different simulations (e.g. 1σ, 5.5–20.5 km). Wong and Segall (2020) build on this approach using a time-dependent conduit flow model, inverting time series data for extruded dome volume, CO_2 emissions and ground deformation. Their model favours an elongate chamber (width:height=0.13–0.55), at 9–17 km depth (top at 2.9–5.8 km depth). Extracting depths from their contours on their Fig. 8 to allow direct comparison with Anderson and Segall 2013) yields depths of ~5–17 km.

Summary and Future work: Relative to the rest of the Cascade arc, magma storage depths are well constrained at Mount St. Helens, with various methods delimiting a vertically extensive magmatic system ranging from ~5–12 km depth (Pallister et al., 2017). In general, the shallower geophysical anomalies cluster at ~2–4 kbar, which is reasonably consistent with the median pressures from mineral barometry, while MIs appear to record shallower processes, perhaps during ascent towards the surface. However, given experimental and MI evidence for the importance of CO_2, it would be worthwhile re-evaluating the CO_2 budget of Mount St. Helens MIs to account for any CO_2 which has partitioned into the vapor bubble. Further MI work on more mafic cones in the general area may provide petrological evidence for the geophysically imaged mid-crustal anomaly. The recent densification of three component broadband stations will greatly increase the potential for local, passive-source inversions. The biggest unanswered question revolves around whether the shallow low velocity anomaly of Waite and Moran (2009) was an ephemeral feature which was difficult to resolve by other methods, or whether it was an imaging artefact.

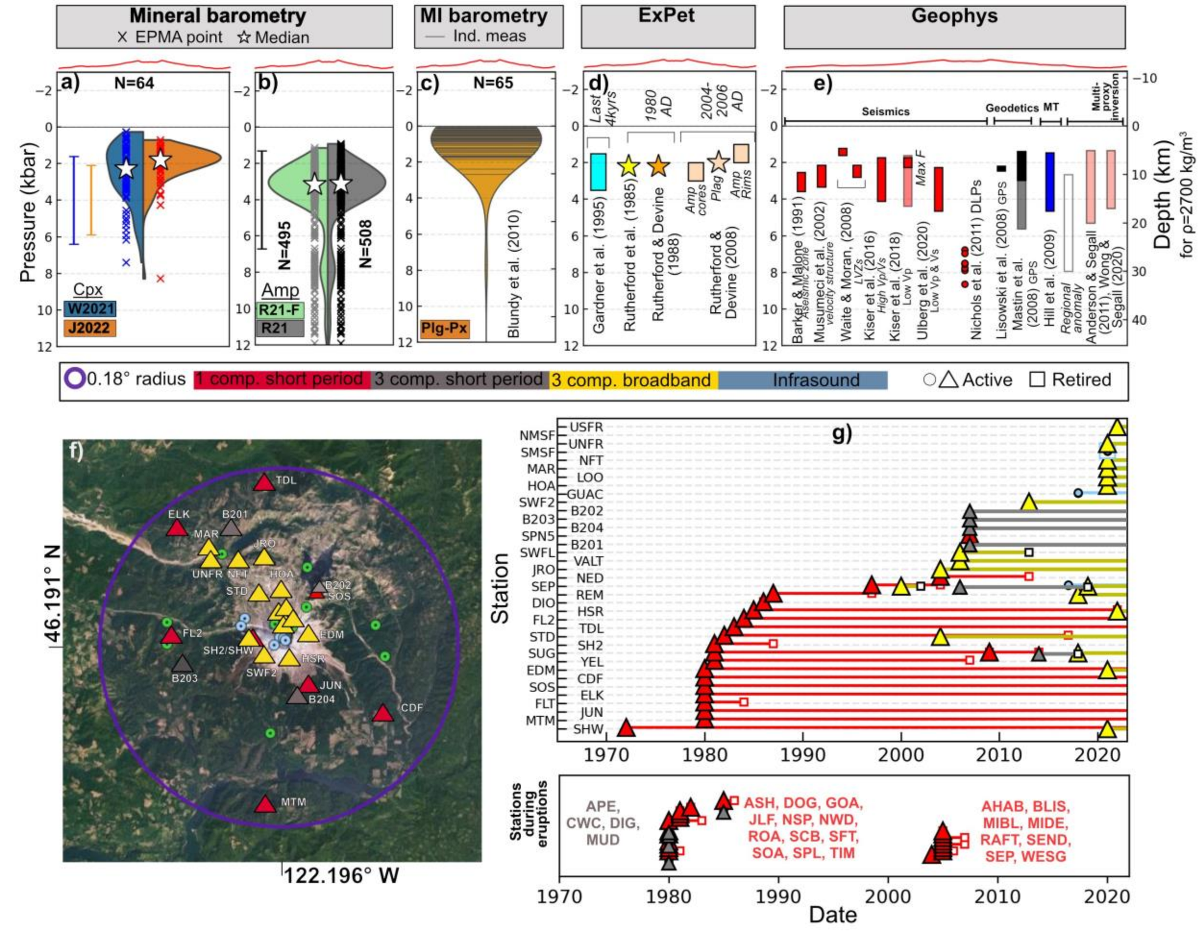


Figure 10 – **Compilation of magma storage depths at Mount St. Helens (a-e) and summary of the seismic network (f-g).** The red line shows the height above sea level across an approximately W-E section spanning 15 km transecting the summit.

Mount Adams

Mount Adams is an andesitic-dacitic stratovolcano, located east of Mount St. Helens along the main arc-axis. The large edifice lies in the centre of a larger volcanic field with ~120 spatter, scoria cones, and shield volcanoes. Vents within ~6 km of the summit are classified as flank vents because of compositional similarity to summit lavas, while those further away have basaltic or basaltic-andesitic compositions (Hildreth, 2007).

Mineral Compositions: J. Fierstein supplied previously unpublished analyses for N=45 Amp and N=1219 Cpx from the post-glacial (0–15 kyr) period of Mount Adams (samples discussed in Hildreth and Fierstein, 1997). The median Cpx-only pressure is ~0.4 kbar for W2021 and ~1.3 kbar for J2022, which is a similar offset to that seen between these barometers at other edifices. In contrast, Amp-only pressures span a significantly greater range, from ~2-6 kbar, with a median pressure of 3.9 kbar.

Experimental phase equilibrium & Melt Inclusions: We are not aware of any phase-equilibrium constraints for Mount Adams or MI studies.

Geophysics: Apart the regional mid crustal anomalies discussed above, there are no seismic constraints for magma storage at Mount Adams, reflecting the fact there is only a single 1 component short period seismometer installed in the area (Fig. 11d), and no detailed local studies have been performed. The iMUSH array extends to the western flanks of Mount Adams, and does indicate potential for melt storage in the lower crust west of Adams (Kiser et al., 2016; Crosbie et al., 2019; Ulberg et al., 2020). However, the lack of stations on or east of the summit, due to permitting constraints, makes it difficult to image a proximal magma system. In addition, no ground based geodetic studies have been performed at Mount Adams, and while InSAR shows coherence, there were no obvious signals of deformation in the 1990s to early 2000s (Poland et al., 2017).

Summary and Future work: The absence of upper crustal geophysical constraints, MIs and experimental petrology is very concerning, particularly given Mount Adams is classified as high threat, and ranked the 34th most hazardous US volcano. While the difference in Cpx-only and Amp-only pressures may reflect different storage regions with different crystallizing phases, these barometers are too imprecise to be sure without other proxies for magma storage. A densified seismic network would be an important next step, along with more focused petrological studies specifically targeting magma storage depths (e.g., MIs).

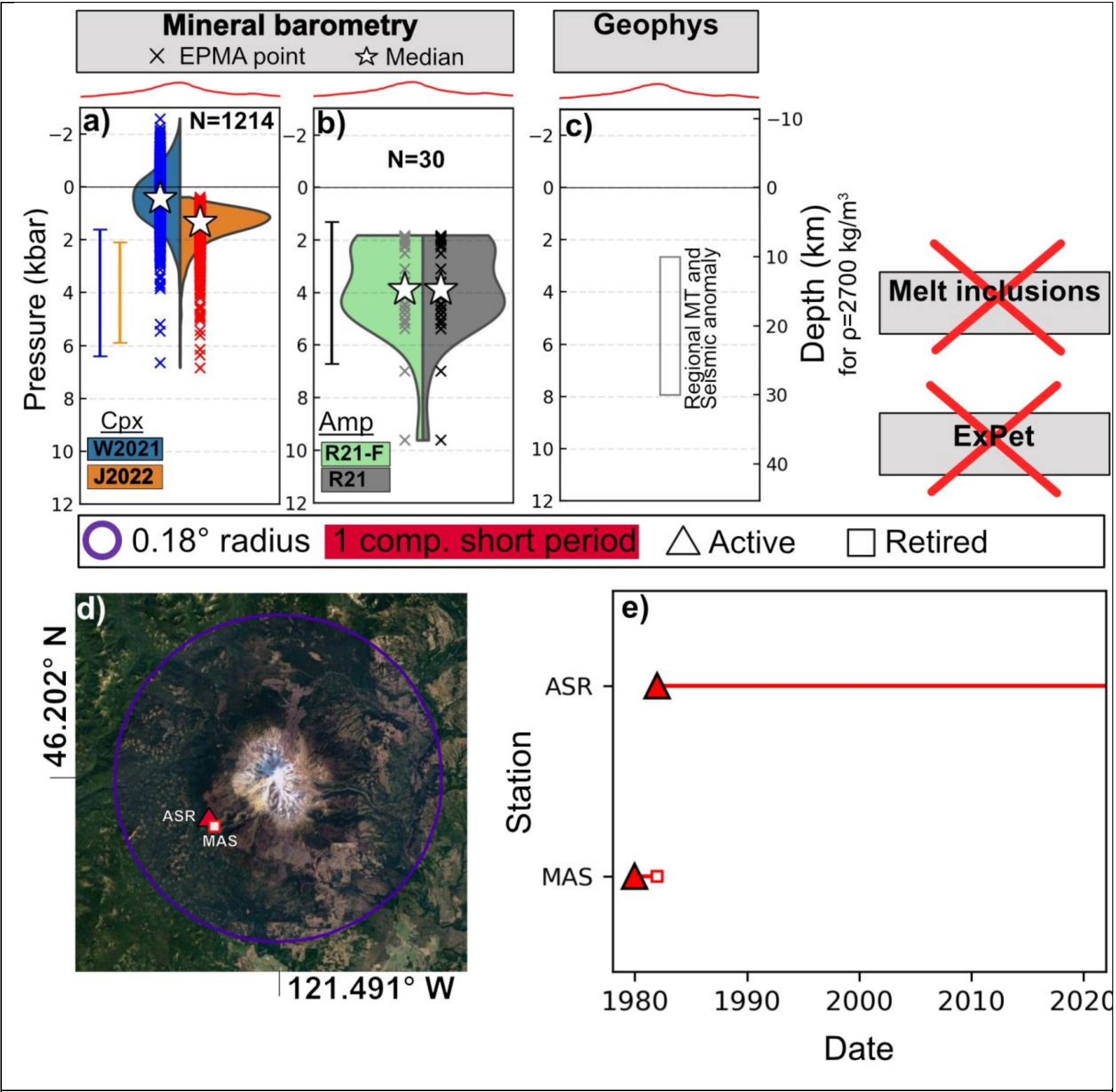


Fig.11. **Compilation of magma storage depths at Mount Adams (a-c) and summary of the seismic network (d-e).** The red line shows the height above sea level across an approximately W-E section spanning 15 km transecting the summit.

Mount Rainier

Mount Rainier is the highest elevation Cascade peak, although the volume of volcanic material is smaller than it appears (130 km^3 vs. 450 km^3 for Mount Shasta), as a result of it being built ontop of older underlying terrains. It is made predominantly of pyroxene andesites-dacites with minor amphibole (59–66 wt% SiO_2; Hildreth, 2007). Unlike other Cascade volcanoes with numerous peripheral vents, Rainier's activity primarily occurs on the main edifice. While lava flows dominate, two large pumice falls >10 km^3 from ~190 ka and ~380 ka have been identified as well as ~10 post-glacial pumice deposits (Hildreth, 2007; Mullineaux, 1974; Sisson and Lanphere, 2000; Sisson and Vallance, 2009).

Mineral Compositions: We obtain the following mineral analyses:

- N=12 Cpx and N=5 Amp analyses from the large andesitic Burroughs Mountain lava flow, which is thought to have been emplaced at ~496 kyr at the beginning of activity at the modern edifice of Mount Rainier (Stockstill, 1999).
- Representative analyses (N=5 Cpx and N=4 Amp) from Venezky and Rutherford (1997, N=5 Cpx, N=4 Amp) from the 2.2 ka tephra layer

- Unpublished EPMA analyses (N=13 Amp, N=35 Cpx) from the Sunset Amphitheatre dacite (~85 ka, see Sisson et al. 2019), cognate plutonic blocks from other Rainier lava flows (T. Sisson, Pers. Comms), and Cpx (N=27) and Amp (N=9) from K-rich spessartite samples, which occurs in small eruptions on the flank and vent, and are thought to bypass the main plumbing system (Sisson et al., 2014).

Considering all formations together, the median Cpx-only pressure is ~2.7 kbar using W2021 and ~2 kbar using J2022. While the number of analyses is relatively small for each formation, Cpx-only pressures from the spessartite samples are deeper than the mafic Sunset Amphitheatre samples (median of 4.4 vs 2.2 kbar using W2021, 2.9 kbar vs. 1.4 kbar using J2022, Supporting Fig. S5). This is consistent with the hypotheses that these spessartite melts bypass the main plumbing system. Burroughs Mountain shows a very broad distribution of pressures, overlapping with Sunset and spessartite samples (-2 to 10 kbar, Supporting Fig. S5a). For Amp-only barometry, the median pressure for all samples is 3.1 kbar. Only two spessartite-hosted Amp pass the quality checks of Ridolfi (2021) – these return pressures which are ~1-2 kbar deeper than Sunset Amphitheatre amphiboles, although far more analyses per formation than could be obtained from the literature are required to accurately resolve any differences in magma storage using mineral compositions (Supporting Fig. S5b).

Experimental phase equilibrium: Venezky and Rutherford (1997) investigate natural products from the 2.2 ka tephra layer C from Mount Rainier, and conduct experiments at 0.25–2.5 kbar. They interpret the products of this eruption to form during mixing of an andesitic and dacitic magma. Their experiments on a powdered Rainier dacite show that the matrix glass composition is produced at H_2O-saturated conditions at <0.5 kbar (~2.4 km). Determining the storage conditions of the andesitic melt is harder (see discussion in MI section below), although they suggest that the presence of Amp indicates storage at >7 km depth, which is reasonably consistent with the Amp-only pressures we obtain.

Melt Inclusions: We are not aware of any published MI work measuring both CO_2 and H_2O. Venezky and Rutherford (1997) describe an “exhaustive” attempt to find suitable MIs, noting that most inclusions were either too small to analyse, or were partially crystallized. They analyse 20 Plag- and Pyroxene-hosted MIs in the dacitic magma, obtaining H_2O contents of 2.4–3.3 wt% by volatiles by difference. For the andesitic magma, they obtain 4–6 wt% (although they acknowledge possible issues due to post-entrapment crystallization). These H_2O contents were used to infer entrapment depths of ~2.4 km for the dacite, and >7 km for the andesite. However, volatile-by-difference methods are associated with large uncertainties (Hughes et al., 2019). Additionally, ongoing MI work indicates that Rainier melts are relatively CO_2-rich and H_2O-poor (T. Sisson, Pers. Comms), so we do not believe it is insightful to calculate H_2O-only saturation pressures based on volatile-by-difference methods.

Geophysics: Moran et al. (1999) investigate P-wave velocities using a local earthquake tomography imaging experiment. They identify a ~10–15 km wide low velocity zone at 1–14 km bsl. Based on the P-wave speeds (6 km s^{-1}) and the absence of earthquakes within this cylindrical anomaly, they suggest that this anomaly consists of hot fractured rock with the possible presence of small amounts of melt and fluid. The absence of significant S-wave attenuation indicates that no large, continuous bodies of melt or fluid exist in this volume.

McGary et al. (2014) use data from the CAFE (Cascade Array for Earthscope) experiment, which collocated seismic and magnetotelluric data in a E-W transect passing near Mount Rainier. While they mostly image the deeper structure down to the subducting slab, they do image a crustal conductor they infer to represent a magma reservoir. However, this feature is offset 6–10 miles from the volcanoes summit, so further investigation of this feature is warranted to determine whether it is magma or another source of conductivity (Bonner, 2015). Obrebski et al. (2015) jointly inverted receiver functions and ambient-noise-derived phase-velocity dispersion curves. No unambiguous low-velocity bodies were detected in the upper crust, although signals were complicated and station spacing of > 10 km probably cannot resolve a magma body the size of that imaged by Moran et al. (1999). There are also 18 LP earthquakes located by Nichols et al. (2011).

From a geodetic perspective, no deformation has been detected at Mount Rainier since at least the 1980s, despite numerous levelling and GPS surveys, CGPS sites and InSAR acquisitions (Poland et al., 2017). Overall, these geophysical constraints are reasonably consistent with depths from petrological methods, with no concrete evidence from either method for extensive magma storage below ~6 kbar (or 20 km).

Summary and Future work: Mount Rainier is the 3rd most hazardous volcano in the US (Ewert et al. 2018, Fig. 1), and while a lot of the hazard is somewhat decoupled from volcanic activity (e.g. edifice collapse, lahars from existing materials), its proximity to the major population centers of Seattle, Yakima, Tacoma and Portland should justify further petrological and geophysical study. Specifically, MI studies could provide insights into the storage conditions of the andesitic melt, perhaps focusing on the pumice deposits documented by Sisson and Vallance (2009). The recent densification of the seismic network (Fig. 12f) should help to further constrain the origin of seismic anomalies beneath Mount Rainier, and determine whether or not these reflect melt.

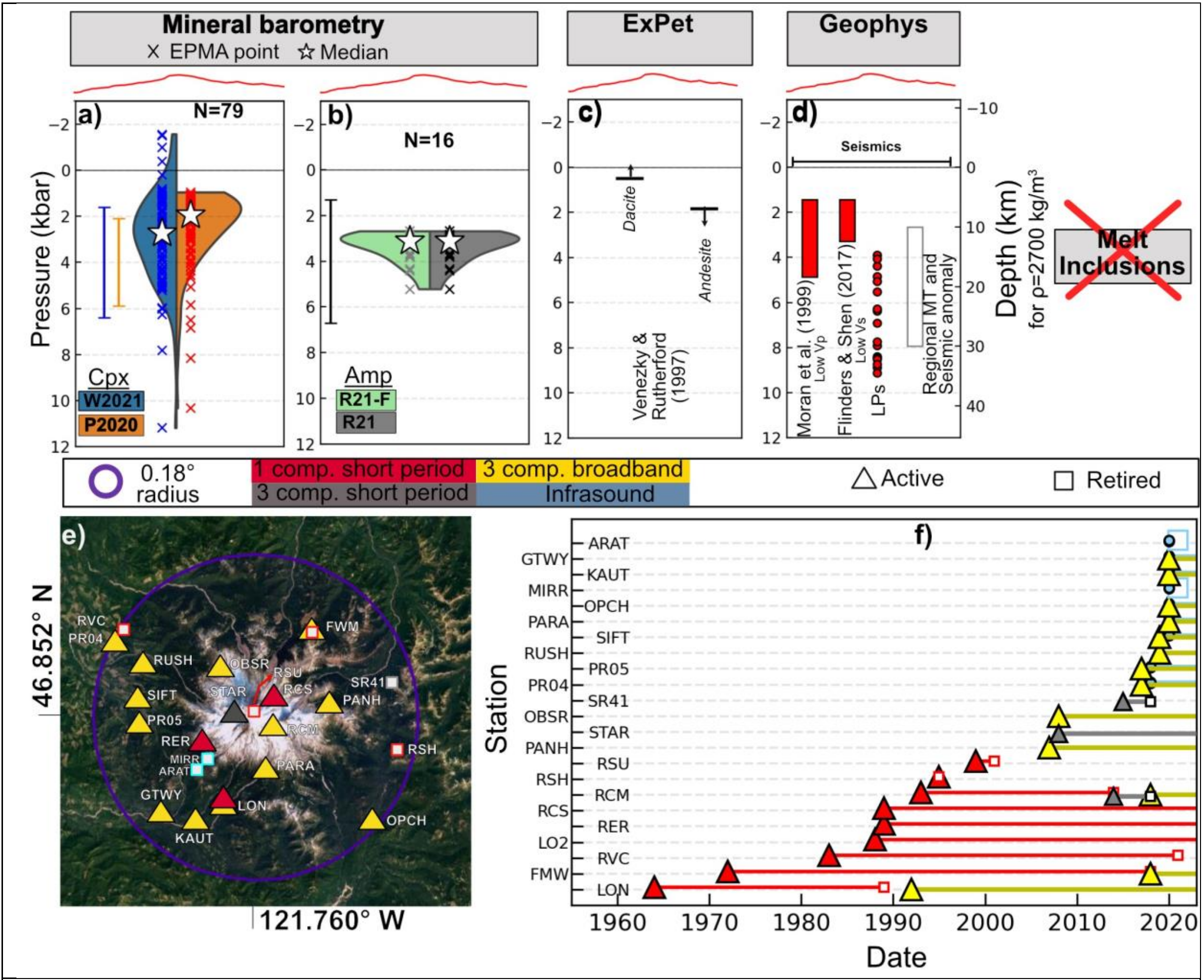


Figure 12. **Compilation of magma storage depths at Mount Rainier (a-d) and summary of the seismic network (e-f).** The red line shows the height above sea level across an approximately W-E section spanning 15 km transecting the summit.

Glacier Peak

Glacier Peak is a predominantly dacitic edifice that has substantially less topographic prominence above neighbouring peaks than many US Cascade volcanoes (Fig. 13d). The early history of Glacier Peak was eroded during the last major glaciation. Since glacial retreat at ca. ~15 ka (Waite et al., 1995), Glacier Peak has produced at least 9 pumice layers indicative of large explosive eruptions and past eruptions have been characterised by numerous lahars. Thus, its activity more closely resembles Mount St. Helens rather than the many other effusion-dominated Cascade volcanoes.

Mineral Compositions: We were only able to obtain N=19 Cpx compositions from the Lightning Creek high magnesian basaltic andesite from Sas et al. (2017). The median Cpx-only pressure is ~2.2 kbar for both W2021 and J2022.

Melt Inclusions: Shaw (2011) measure 16 olivine-hosted MIs from a primitive calc-alkaline basalt and a primitive low-potassium olivine tholeiite cinder cone (data reported in Venugopal et al., 2020). However, Shaw (2011) did not measure CO_2 in MI vapour bubbles. Venugopal et al. (2020) make a prediction of the amount of bubble CO_2 by assuming the same proportion of melt-vapour partitioning as at their measurements at Mount Meager. However, the partitioning of CO_2 into a vapour bubble is very dependent on the amount of PEC varies to a large extent even within a single eruption (Wieser et al. 2021, 2023c), let alone between volcanoes. Thus, we favour stating minimum estimates using just glass volatile contents from Shaw (2011) rather than using the bubble reconstructions of Venugopal et al. (2020).

Experimental phase equilibrium: We are not aware of any phase equilibrium experiments relevant to Glacier Peak.

Geophysics: We are not aware of any geophysical constraints on magma storage, other than identification of 8 LP earthquakes (Nichols et al., 2011). There is only a single one-component short-period seismometer, so the lack of seismic constraints other than LPs is not surprising (Fig. 13). No ground-based geodetic studies have been attempted, and InSAR hasn’t detected any deformation (although the ice-covered summit and heavily vegetated flanks make coherence challenging; Poland et al., 2006).

Summary and Future work: Glacier Peak is ranked as very high threat, and the 15th most hazardous US volcano. The absence of petrological or geophysical constraints on magma storage is a very clear data gap to address with future work.

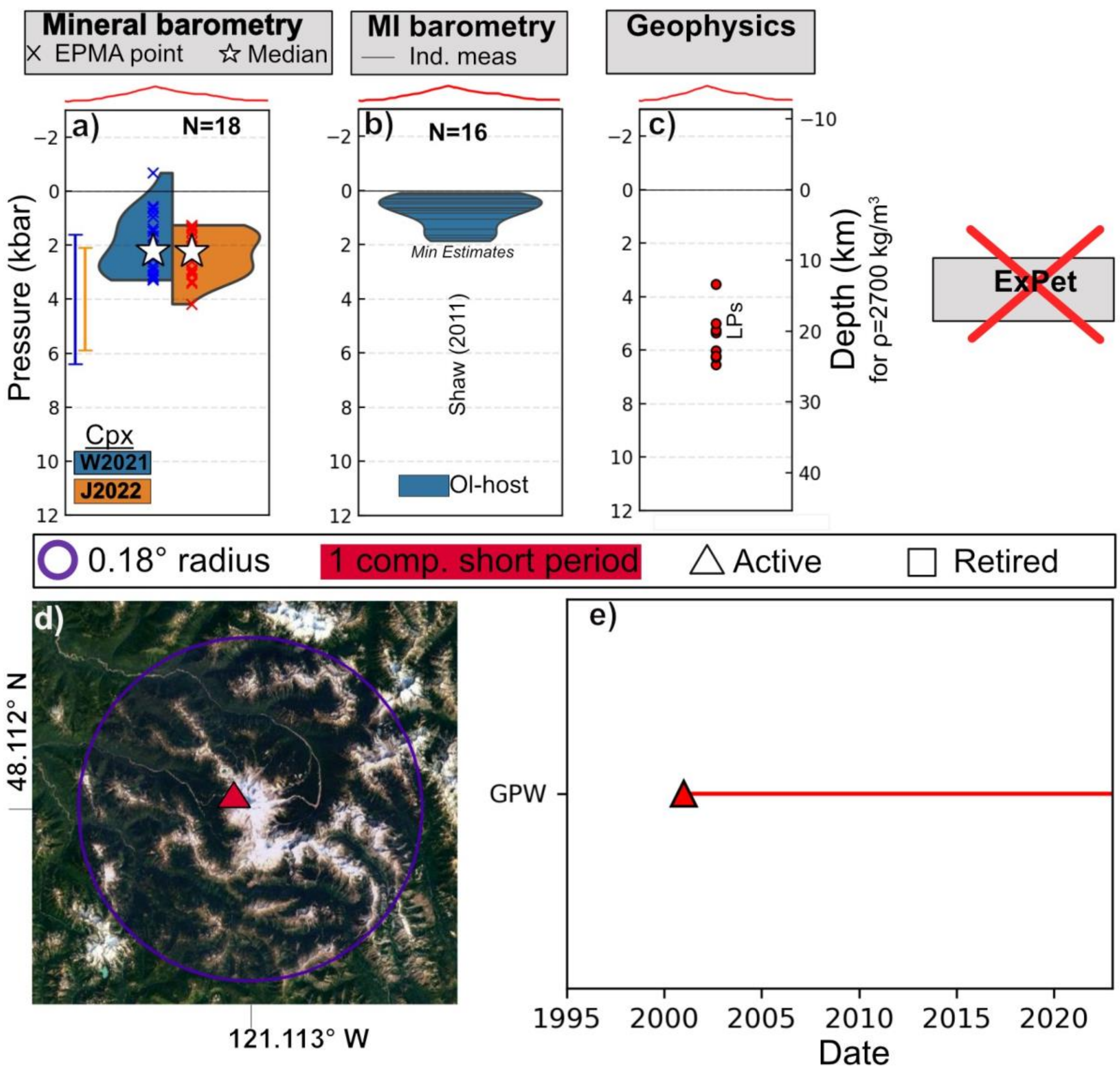


Figure 13. **Compilation of magma storage depths at Glacier Peak (a-c) and summary of the seismic network (d-e).** The red line shows the height above sea level across an approximately W-E section spanning 15 km transecting the summit.

Mount Baker

Mount Baker is a stratocone situated within a larger multi-vent volcanic field that has been active since 1.3 Ma. It is one of the youngest volcanoes in the Cascades, with most of the modern edifice built over the last 40 ka (Hildreth et al., 2003). The larger volcanic field is predominantly andesitic and rhyodacitic in composition, with basalt and dacite making up only ~1–3% of the total volume. Mt Baker itself comprises of andesites, two pyroxene dacites, with some olivine-bearing andesites (Hildreth et al., 2003)

Mineral Compositions: We obtained the following mineral analyses:

- N=12 Amp and N=133 Cpx reported in Gross (2012) from three mid Pleistocene dacitic lava flows Nooksack Falls (~149 ka), Cougar Divide (~613 ka) and Mazama Lake of uncertain age (Hildreth et al., 2003).
- Cpx from the more primitive basalts and Mg-rich andesites erupted at Mount Baker, with N=17 Cpx from Baggerman and DeBari, (2011), N=32 Cpx from Sas et al. (2017), N=28 Cpx from Mullen and McCallum, (2014), and N=26 Cpx from Moore and DeBari, (2012).

The median Cpx-only pressure is 2.4 kbar for W2021 and 1.8 kbar for J2022. There is significant overlap between Cpx from dacitic and more mafic samples, with no consistent differences emerging for both W2021 and J2022 (Supporting Fig. S5). The N=12 Amp from the dacites examined by Gross (2012) yield a pressure of ~2.9 kbar (between the median Cpx pressures of 1.7 and 2.9 kbar from J2022 and W2021 for these dacites).

Melt Inclusions: Shaw (2011) measure 8 olivine-hosted MIs from Mount Baker (reported by Venugopal et al., 2020), with the same caveats regarding CO_2 as described for Glacier Peak. These MIs return pressures between 0–2 kbar, which represent minimum estimates as bubble CO_2 was not directly measured.

Experimental phase equilibrium: We are not aware of any phase equilibrium experiments relevant to Mount Baker.

Geophysics: Seismically, Mount Baker is relatively quiescent, with most shallow (<3 km) events thought to reflect activity of the glacier. We find one abstract describing a local seismic survey conducted at Mount Baker but no clear link to magma storage is made (Rohay and Malone, 1977). The lack of seismic data is unsurprising given the sparse coverage of the seismic network. At the time of writing, there is only a single three component broadband seismometer within 20 km. Nichols et al. (2011) report 31 LPs earthquakes from Mount Baker, more than any other Cascade volcano.

Mount Baker experienced a period of thermal unrest in 1975, investigated retrospectively by Crider et al. (2011). In 1975, a large area of snow-free ground was created in the crater, with high magmatic gas emissions, and an accompanying increase in gravity in the 30 yrs following this period. While there is some debate about whether this episode can be magmatic given the lack of seismicity, Crider et al. (2011) note the presence of recent aseismic intrusions at other arc volcanoes worldwide (e.g., Lu et al., 2000), indicating that an absence of seismicity doesn't necessarily mean an intrusion didn't happen. Unfortunately, there was insufficient monitoring data to place detailed constraints on this episode beyond the speculation that it was likely caused by intrusion into the mid crust.

Hodge and Crider (2010) investigate edifice deflation between 1981 to 2007 recorded by continuous GPS and EDM at Mount Baker. This deflation is best recreated by a source at ~5.8 km depth (basl, ~2000 m), located 1.5 km to the E-NE of the summit. This aligns reasonably well with Cpx-only and Amp-only pressures. Poland et al. (2017) describe challenges relating to InSAR at Mount Baker as a result of poor coherent on the edifice because of ice and snow, and vegetation on the lower flanks, meaning data is only possible to collect over a narrow window in late summer on the mid flanks.

Summary and Future work: The paucity of data for this very high threat volcano is a concern. Mount Baker is an obvious target for MI work given the presence of tephra layers. Experimental phase equilibrium would also help to place constrains on storage conditions. Without a concerted geophysical campaign, it is unlikely that meaningful magma storage information will be gleaned from the current seismic network without significant densification.

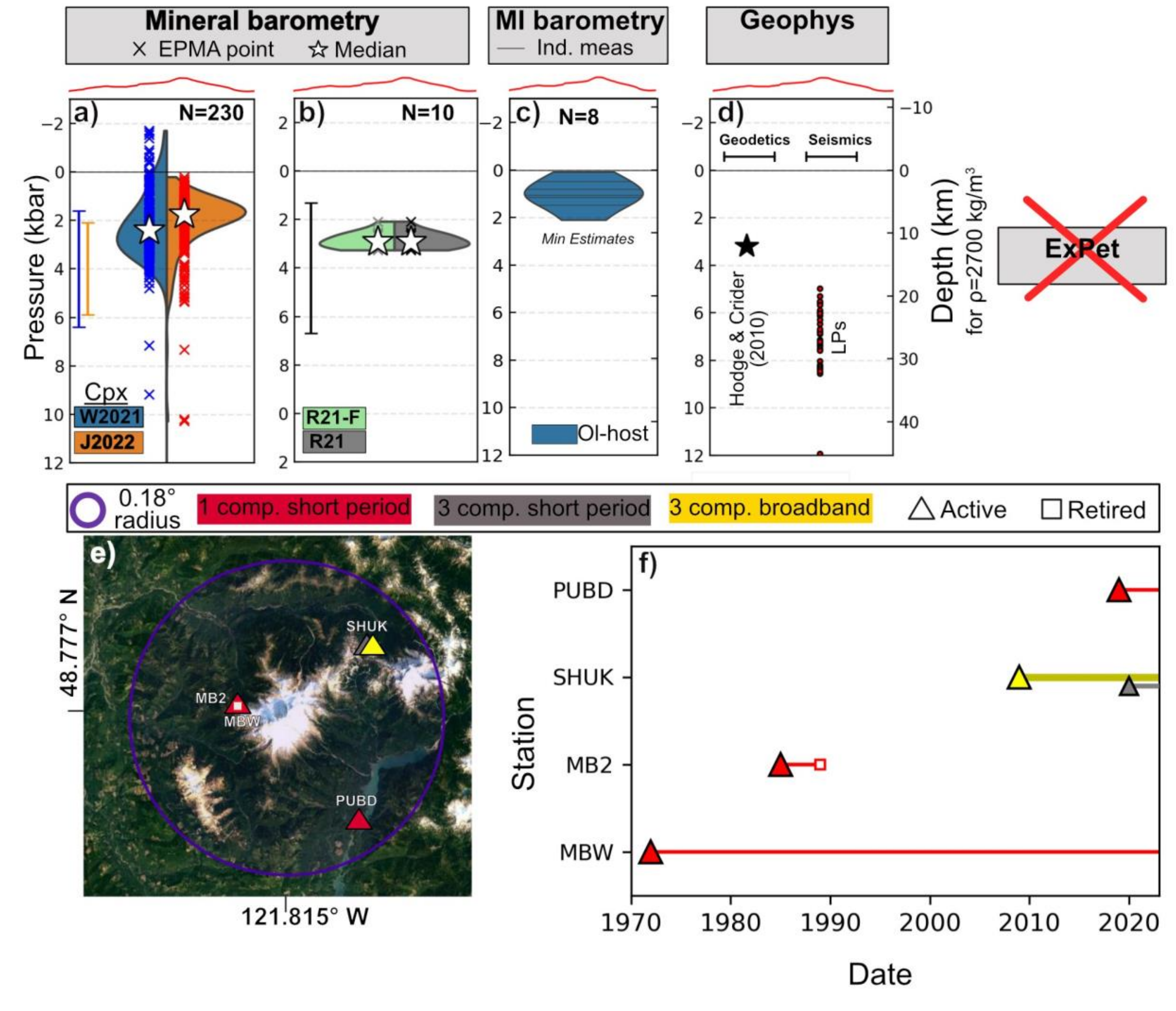


Fig. 14. **Compilation of magma storage depths at Mount Baker (a-d) and summary of the seismic network (e-f).** The red line shows the height above sea level across an approximately W-E section spanning 12.5 km transecting the summit.

Canadian Garibaldi Volcanic Belt:

The Garibaldi Volcanic Belt consists of 2300 distinct vents, and 22 major edifices, including Glacier Peak and Mount Baker (Hildreth, 2007). Here, we focus our discussion of the available data for the Canadian segment of this volcanic belt, given differences in volcano monitoring on either side of the border. The major Canadian edifices include Mount Garibaldi, Garibaldi Lake, Mount Meager, Salal Glacier, Bridge River. A wide variety of compositions are present in this Canadian segment, with dacites and rhyodacites at Mount Garibaldi and Mount Cayley, and high Si rhyolites at Mount Garibaldi (Hildreth, 2007). These volcanoes also erupt olivine-bearing basalts and basaltic-andesites (Venugopal et al., 2020).

Mineral Compositions: We compile N=15 Cpx compositions from basaltic andesite samples from the Garibaldi Lake Volcanic Field (Fillmore, 2014). We were unable to find any other mineral data. W2021 yields median pressures of 0.19 kbar, and 1.8 kbar for J2022.

Experimental phase equilibrium: We are not aware of any experimental phase constraints on magma storage conditions in the Garibaldi Volcanic Belt.

Melt Inclusions: As mentioned in the introduction, Venugopal et al. (2020) perform glass and vapour bubble measurements, but do not perform an instrument specific Raman calibration. Given that their high CO_2 densities are thermodynamically impossible at room temperature, it seems highly likely the amount of CO_2 in the vapour bubble was overestimated. We show their vapour-bubble reconstructed

CO_2 alongside glass-only saturation pressures for completeness. Re-analysis of a subset of bubbles could be used to correct the original Raman data (as different Raman calibrations are reasonably parallel to one another, Lamadrid et al., 2017).

Geophysics: There are no geodetic constraints on magma storage in the Garibaldi Volcanic belt. No-ground based geodetic studies have been performed, and while C-band InSAR obtains some coherent images on the volcanoes flank, InSAR is generally hindered by vegetated slopes and ice-covered summits (Poland et al., 2017). We do not find any direct seismic constraints on magma storage beneath these volcanoes. Querying the IRIS database from 1975-2023 for the Canadian networks yields 4 seismometer stations in the general vicinity of the Garibaldi Volcanic Belt. The broader distribution of vents and less well defined summits relative to the US Cascades makes it harder to define clear query criteria. Instead, we show volcanic regions on Fig. 15. There is a 3bb station close to Whistler (WSLR, 2013–present), and a second 3bb station is present near Squamish (WPB), ~27 km south of Mount Garibaldi (1bb 1996–2018, 3bb 2018–present). There was a 3bb station ~8km W of Mount Meager and 10–15 km SW of Salal Glacier between 2016–2019, and a 3bb station about ~20km ESE along the same river valley from 1993–1998, although it appears there are currently no stations in this area. Lu and Bostock (2022) use the record from these 4 stations to identify 48 deep long period earthquakes (DLPs) at ~4–45 km depth in the region near Mount Meager.

Summary and Future work: The paucity of work on the Garibaldi Volcanic Belt likely reflects its relative inaccessibility, snow and ice cover, and the lower hazard compared to the more active, US-based volcanoes.

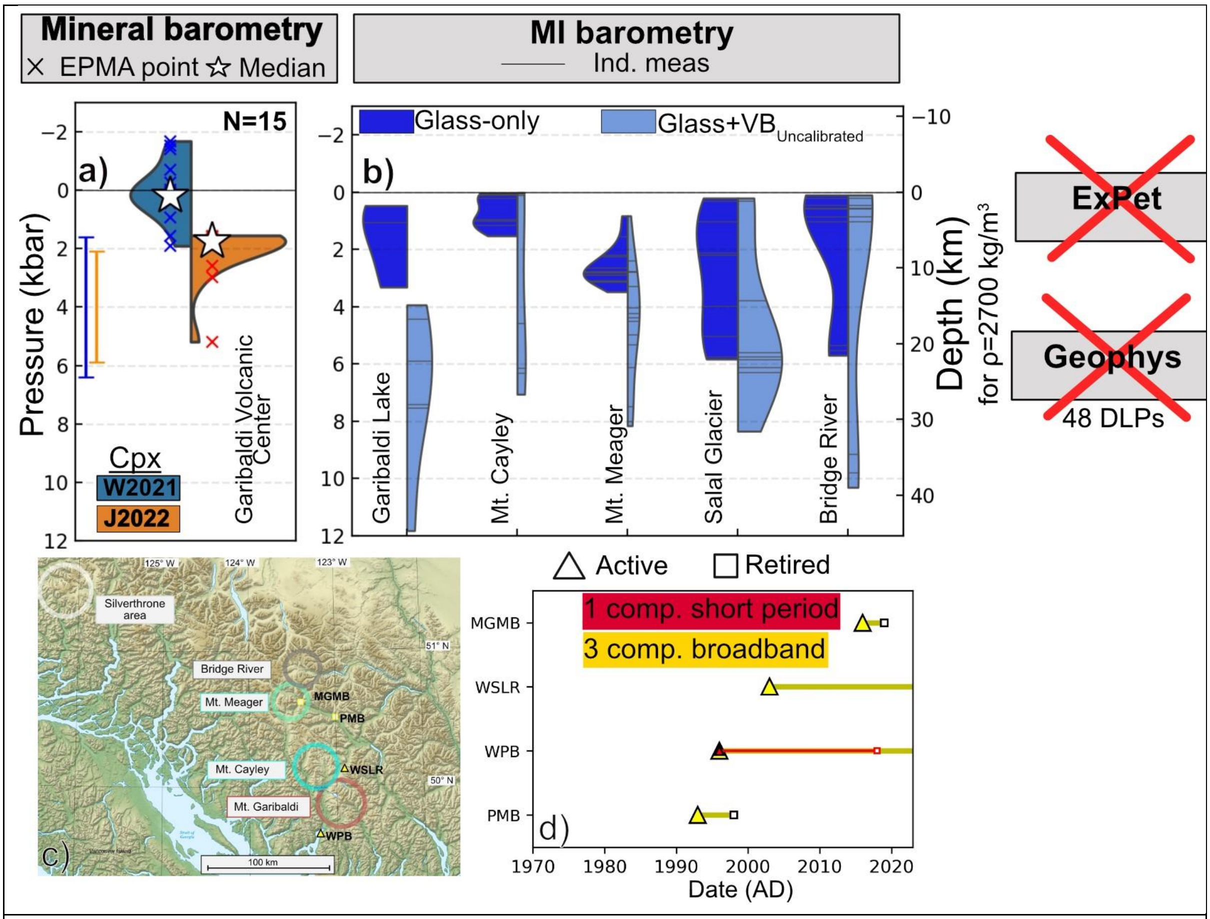


Fig. 15. **Compilation of magma storage depths for the Canadian Garibaldi Volcanic Belt (a-b) and summary of the seismic network (c-d).** Circles in c) show the approximate location of volcanic fields. Map in c) adapted from Sémhur (2007).

Arc-Scale trends

Data Availability

Our compilation shows the presence of many concerning data gaps affecting our knowledge of magma storage depths along the Cascade Arc. The quantity of data available along the arc is highly variable, and is also poorly correlated with the USGS threat index for individual volcanoes (Fig. 1; Ewert et al., 2018). Some systems are relatively well covered, but many high threat volcanoes show a disturbing paucity of geochemical and geophysical constraints on the nature of crustal magma storage. For example, at the second highest threat volcano in the Cascades (Mount Rainier, 3rd highest threat volcano in the US) we have no magma storage depth constraints from MIs, very few reported Amp and Cpx compositions, one experimental pressure constraint, and only two seismic constraints. Recent deployment of 13 broad band seismometers (Fig. 12f) provides potential for better seismological imaging in future (e.g., receiver functions, P and S wave topography). Mount Hood (6th highest threat in US) and Three Sisters (7th highest threat in US) are also very understudied. Available MIs from Mount Hood are limited and potentially unreliable due to SIMS calibration issues, and there are no detailed geophysical or experimental constraints on magma storage depths. Similarly, the Three Sisters have no usable MI data, no seismic studies, and no experimental studies placing precise constraints on magma storage reservoir depths. The only real depth constraints at Three Sisters come from a geodetic inversion of the 1998 inflation episode. However, it has been suggested based on spring chemistry and the lack of surface volcanism <10 ka that numerous intrusions likely occur in the deforming area with a very low probability of eruption (Evans et al., 2004). Thus, it is unclear if these geodetic estimates are providing useful information on the storage depths of melts. In addition, Mount Baker and Glacier Peak, which are both ranked as very high threat (#14 and #15 highest threat in US) have also been greatly understudied from both a petrological and geophysical perspective.

Probable trends

With the caveat of the relatively sparse and variable data coverage, we compile the available geophysical (Fig. 16a) and mineral (Fig. 16b) constraints on magma storage depth as a function of latitude to investigate along-arc trends in magma storage.

From a geophysical perspective, the vast majority of constraints on proximal magma chambers (rather than regional anomalies) are clustered at depths corresponding to ~1–5 kbar, with only magnetotelluric anomalies, LP earthquakes and regional seismic surveys returning higher pressures.

Considering the high imprecision of mineral-only barometers, Cpx-only pressures from J2022 and Amp-only pressures from R2021 are remarkably constant along the arc, although the Amp-only pressures show slightly more scatter. In general, the median pressures from these mineral-only barometers suggest that the vast majority of magma storage occurs in the upper 4 kbar (~0–15 km) of the crust. The general agreement within the ±2–3 kbar uncertainty of Amp and Cpx-based barometers gives us confidence in this result, along with the fact that geodetic and seismic constraints on magma storage generally have depths equivalent to ~0–5 kbar. With the limitations of the reported information, it is difficult to interpret whether the spread of individual calculated pressures for a given volcanic center represents true transcrustal storage or analytical uncertainty (Wieser et al. 2023b).

The general confinement of magma storage estimates at pressures less than 4 kbar has been noted in a recent global compilation of geophysical estimates of magma storage depths in volcanic arcs , cyan histogram, Fig. 16b). Rasmussen et al. (2022) describe a correlation between water contents in melt inclusions from arcs and geophysically-determined magma storage depths, with the relationship between depth and H_2O plotting along the water-saturation curve. They propose two possible explanations: 1) H_2O controls magma storage depth through an increase in viscosity accompanying water exsolution (which they refer to as a 'mantle control') or 2) H_2O is diffusively reset at a depth determined by a 'crustal control'. The authors infer that a crustal control would cause correlations between ratios such as Nb/Ce and Ba/La to be lost, while a mantle control would preserve these relationships. Based on the preservation of strong H_2O-incompatible element ratios in the Aleutians, Rasmussen et al. (2022) favour a mantle control, with primary magmatic water contents controlling magma storage depths.

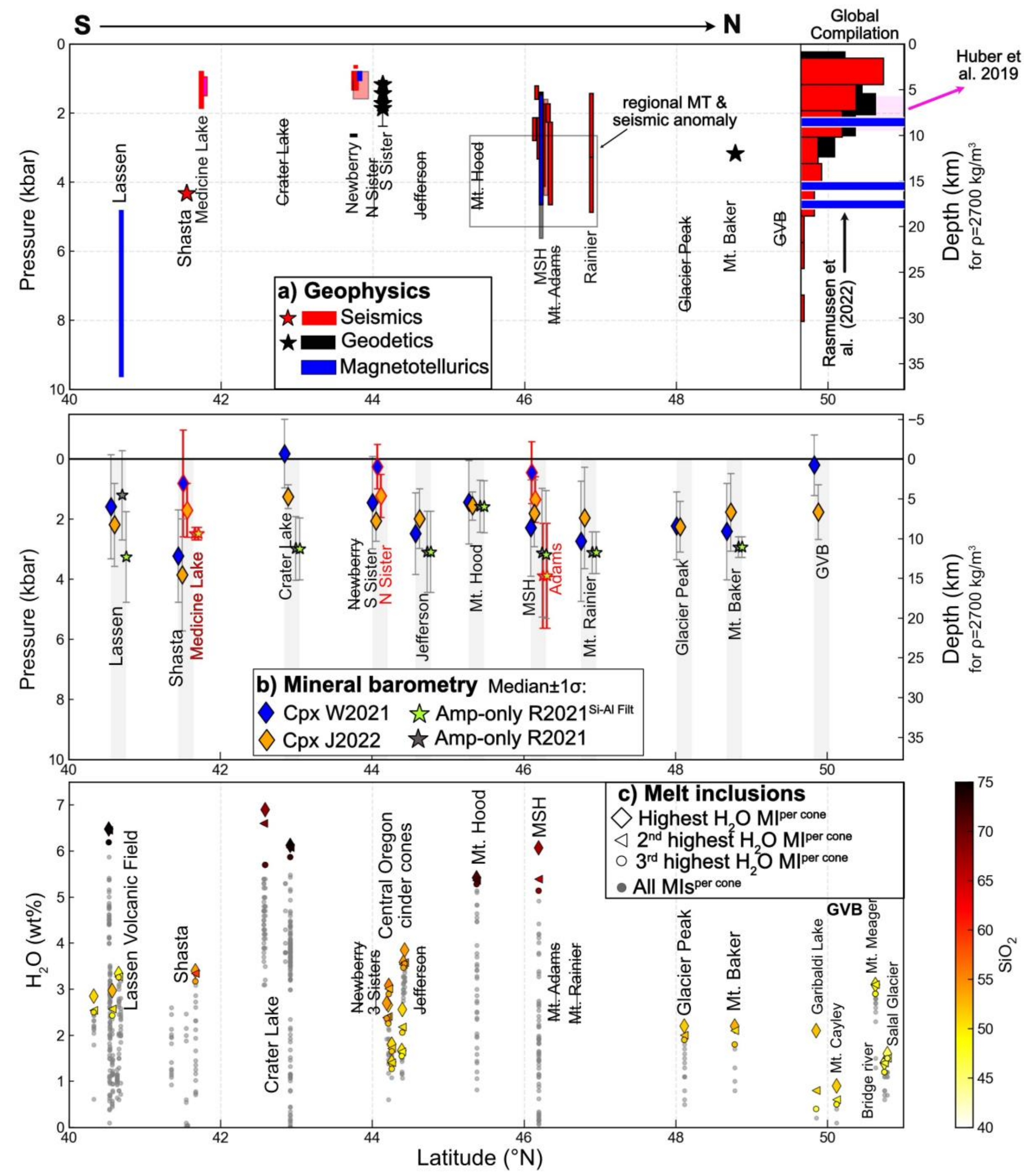


Figure 16: Summary of magma storage depths along the cascades, with the x axis showing approximate latitude (Medicine Lake and Mount Adams are shifted slightly from true latitude to avoid overlap with Shasta and MSH respectively). a) Compilation of geophysics for each center. The histogram shows a global compilation from Rasmussen et al. (2022) using the same color scheme as for the Cascades, and the 2±0.5 kbar from the compilation of Huber et al. (2019). b) Compilation of mineral barometry. Symbols show the median pressure, and errorbars show the standard deviation of calculated pressures for each volcano. Red outlines on symbols are used for Medicine Lake and MSH because of overlaps in latitude with Shasta and Mount Adams. c) H_2O contents from melt inclusions, with the 3 most H_2O-rich melt inclusions from each volcano/cinder cone colored based on the melt inclusion SiO_2 content. Tephra samples collected at different locations but from the same source (e.g., the S17 cone, Mount Shasta) are grouped as one. Volcanoes with no constraints are shown with crossed out text.

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To investigate the hypothesis of Rasmussen et la. (2022), we consider trends in H_2O with latitude along the Cascades, selecting the three most H_2O-rich MIs from each volcanic center (colored diamonds, triangles and circles, Fig 16c) as representative of the H_2O contents most resistant to degassing and diffusive re-equilibration. The relationship of Rasmussen et al. (2022) only applies to mafic magmas, so we color-code the most H_2O-rich melt inclusions by SiO_2 content (Fig. 16c). Unlike compiled magma storage depths, H_2O contents in the most mafic samples (yellow and orange colors) show considerable variation along strike.

When considering all melt inclusion compositions, a strong positive correlation is present between SiO_2 and H_2O contents (Supporting Fig. S3). If a H_2O-saturated mafic magma stalls in the crust and differentiates (as in the model of Rasmussen et al. 2022), the H_2O content in the melt would track the change in volatile solubility from basalt to rhyolite. However, different solubility models show vastly different trends in H_2O solubility over this differentiation interval (see Wieser et al. 2022c, Fig. 10), with none predicting an increase as large as that observed here (Fig. S3). Instead, this relationship between SiO_2 and H_2O is more indicative of differentiation in the presence of an exsolved fluid which is relatively CO_2-rich, meaning that CO_2 initially dominates the vapour phase, so H_2O behaves relatively incompatibly during fractional crystallization (Wieser et al., 2022c). This is supported by calculated X_{H2O} values for Cascade mafic melt inclusions (Supporting Fig. S10), which indicate that the exsolved fluid is dominated by CO_2, particularly for melt inclusions where the vapour bubble is accounted for. This is not consistent with the model inferred by Rasmussen et al. (2022), which assumes the volatile system is dominated by a H_2O-rich vapour phase at the point of magma stalling.

Thus, we suggest based on our compilation that it is more likely that a crustal process operating along the entire arc (whether due to a rheological boundary, or density-controlled) is restricting storage of all but the most mafic magmas to the upper 0–5 kbar of the crust (Chaussard and Amelung, 2014; Huber et al., 2019). Our compilation does show hints of deeper crustal magma storage, likely of more mafic magmas. However, due to the very nature of magma differentiation itself, crystals from the mafic predecessors to the more evolved erupted liquids are poorly preserved, meaning deeper magma storage is easily obscured. This preservation bias is particularly hard to see through given the small number of published mineral compositions at many Cascade volcanoes (e.g., N=18 Cpx from Glacier Peak, N=16 Amp from Mount Rainier, N=11 Cpx from Three Sisters). If we imagine that 1% of deeper formed crystals are erupted, we would need thousands of analyses to get a cluster of deeper pressures that we would be able to intepret with confidence, rather than appearing as outliers. Petrologic experiments on predecessor mafic magmas erupted at the periphery of Mount Shasta and Mount Rainer do support a period of mid- to lower-crustal storage that results in crystallization (e.g., Krawczynski et al., 2012) and/or crustal melting (e.g., Blatter et al., 2017, 2013), which is likely important to evolve mantle-derived magmas to the intermediate and silicic compositions characteristic of those stored in the upper crust. Future MI work measuring both the melt and vapour bubble, petrologic experiments, and substantially more mineral analyses are thus required to further investigate the prevalence of deeper storage of mafic melts in the Cascades arc relative to the ubiquitous upper crustal reservoirs recorded by the compiled geophysical studies and available mineral data.

Conclusions

A detailed review of available petrological, geochemical and geophysical constraints on the depth of magma storage beneath Cascade arc volcanoes suggest that the majority of magma storage is restricted to the upper 0–5 kbar (0–20 km) of the crust, and at reasonably constant depth along strike. However, further consideration of magma storage at higher resolution, and evaluation of latitudinal variations is limited by issues with accuracy and by high uncertainties of techniques used for estimating storage pressure, and by numerous data gaps that exist along the arc. Considering the number of high-threat volcanoes in the Cascades, the paucity of data to constrain magma storage from geochemical and geophysical perspectives is highly concerning, and a stark contrast to other high-threat volcanoes in the US (e.g., Kilauea, Poland et al., 2014).

Gaps in geophysical datasets result from: 1) difficult access because of terrain, snow and ice cover, 2) the fact many Cascade volcanoes have been relatively quiescent in the last few decades, 3) dense geophysical imaging campaigns are costly and uncommon, and 4) permitting issues in wilderness areas hindering the establishment of dense monitoring networks (Moran and Benjamin, 2021; Poland et al., 2017). Gaps in geochemical and petrological datasets reflect a lack of study of many important systems, specific technique limitations (e.g., neglecting CO_2 vapour bubbles, poor quality EPMA analyses of mineral compositions, Wieser et al., 2023b), and poor data reporting (e.g., publishing only representative mineral analyses). We therefore recommend targeted melt inclusion, petrologic, experimental and further geophysical studies of the understudied high threat volcanoes in the Cascades arc to determine their depths of magma storage, which are critical for interpreting future monitoring signals and will influence the style, size, and frequency of future eruptions.

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Open Research

A compiled dataset of mineral compositions, melt inclusions and seismic stations, along with the Jupyter Notebooks used to compile, filter and plot data are available on Penny Wieser's GitHub (https://github.com/PennyWieser/Cascade_data_Compilation/tree/main). Upon article acceptance, this will be archived on Zenodo.

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