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ABSTRACT

Over the last decade, the melt embayment has proven its merit as a robust petrological tool capable of recording magma decompression rates for explosive eruptions. However, the models developed and applied to extract this information from embayments have not accounted for the complexity and nonlinearity of magma flow in the conduit. We present Embayment Decompression in Two Stages (EDiTS): a numerical model for extracting magma decompression rates from measured volatile diffusion profiles preserved in crystal-hosted embayments, approximating magma acceleration using two constant-rate decompression paths. This model solves for three unknown parameters: initial (deeper) and final (shallower) decompression rates, as well as the pressure where a transition occurs. We successfully benchmark EDiTS against existing numerical diffusion models, and use controlled multi-stage decompression experiments on natural quartz-hosted embayments to test the ability of our model to recover known decompression paths. We find that EDiTS is able to closely approximate the known two-stage path in the mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) experiment, while a constant-rate modeling approach is unable to simultaneously fit H_2O and CO_2 gradients. However, in the H_2O -saturated experiment, there is no unique solution to the resulting gradient, with both constant-rate and two-stage models reproducing the measured profile, and EDiTS notably overestimating the known total ascent time by several hours. Using decompression experiments, we show that constant-rate models can provide misleadingly good fits to embayment H_2O gradients produced by more complex decompression histories, and thus the measurement and modeling of multiple diffusing species, when available, can provide crucial constraints. We then apply EDiTS to re-evaluate mixed-volatile embayment datasets from explosive silicic arc and caldera-forming eruptions from five volcanic centers (Yellowstone, WY, USA; Valles, NM, USA; Long Valley, CA, USA; Taupo, NZ; Mount St. Helens, WA, USA). In contrast to the minutes to hours of total ascent time extracted from embayment volatile profiles using constant-rate models, our two-stage model resolves slower initial ascent times that span 3.5–11 h. Final ascent rates are 1–2 orders of magnitude faster than the initial extracted rates, in agreement with theoretical conduit flow model predictions. Reassessment of embayments from the May 18th, 1980 eruption of Mount St. Helens results in an initial stage of ascent consistent with the timing of magma arrival at the surface from the seismically-inferred storage region (7–9 km) ~3.5 h after the initial blast, and a final stage of ascent (<1–5 min) in close agreement with time-integrated bubble number densities. Our combined numerical and experimental results, and reevaluation of natural datasets, suggest that, with the application of advanced models, the melt embayment can provide a more nuanced picture of magma decompression timescales from the deep conduit to the surface.

1. Introduction

Magma ascent through the volcanic conduit is a dynamic process, governed by complex feedbacks between intrinsic magma properties (e.g., viscosity, density, crystallinity, vesicularity) and external controls (e.g., conduit wall shearing, conduit geometry, etc.) (e.g., [Gonnermann and Manga, 2013](#)). One critical factor driving acceleration and explosive fragmentation of high-viscosity rhyolitic magmas is the interaction

between magma decompression, volatile exsolution and melt-coupling, buoyancy, and resulting overpressure (e.g., [Sparks, 2003](#)). Recent numerical conduit models have implemented time-dependent, non-steady-state solutions to account for this dynamic feedback between magma flow, conduit properties, and reservoir pressure (e.g., [Melnik and Sparks, 2006](#); [Wong and Segall, 2019](#); Fig. 1a). Advances in numerical techniques applied to modeling pyroclast textures (i.e., bubbles, crystals) have followed suit, with incorporation of time-dependent

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decompression in models aimed at reproducing crystal size distributions (CSD), microlite number densities (MND), and bubble number densities (BND) observed in natural samples (Andrews and Befus, 2020; Hajimirza et al., 2021). These models have expanded upon earlier efforts that applied a step-function (Hammer and Rutherford, 2002) or constant-rate (Toramaru, 2006) boundary condition to extract decompression rates. This time-integrated approach to modeling pyroclast textures has allowed for seemingly decoupled, speedometer-specific decompression rates spanning >4 orders of magnitude to be more closely reconciled, as recently demonstrated for the 2008 eruption of Chaitén in Chile and the 1991 eruption of Mount Pinatubo in the Philippines (Hajimirza et al., 2021; Harris et al., 2024). The same treatment, however, has not been extended to all petrological tools used to infer magma decompression rates, limiting the comparability of results between different ascent rate meters and our ability to resolve nuanced decompression histories. One such recorder frequently leveraged to estimate magma decompression rates (14 published studies applied to 27 eruptions from 14 volcanic centers; Table 1) but still confined to the realm of constant-rate modeling is the melt embayment (open melt pocket or inclusion).

Over the last decade, embayments have gained a foothold among petrological recorders used to estimate magma decompression rates in explosive volcanic eruptions (Liu et al., 2007; Humphreys et al., 2008; Lloyd et al., 2014; Ferguson et al., 2016; Myers et al., 2018, 2021; Moussallam et al., 2019; Newcombe et al., 2020; Geshi et al., 2021; Befus et al., 2022; Saalfeld et al., 2022; Zuccarello et al., 2022; Elms et al., 2023; Harris et al., 2024). The premise behind this technique is that as magma ascends, dissolved volatiles (H_2O , CO_2 , S, Cl, F) diffuse through melt embayment channels in response to decompression-induced degassing of the surrounding melt and the consequent formation of a bubble at the outlet of the embayment (Fig. 1b). This generates

a chemical potential gradient between the embayment interior and outlet, where the presence of the bubble implies a boundary layer of melt with a volatile concentration fixed at the solubility-predicted, equilibrium value. Upon eruption and explosive fragmentation, embayment melt rapidly quenches to glass, locking in compositional gradients that are measured using microanalytical techniques (e.g., nano secondary ion mass spectrometry: Lloyd et al., 2014; Newcombe et al., 2020; Raman spectroscopy: Myers et al., 2021; Zuccarello et al., 2022; Fourier transform infrared spectroscopy, Myers et al., 2018) or other novel methods (e.g., calibrated back-scattered electron grayscale intensities, Humphreys et al., 2008) and modeled numerically to extract decompression rates. Although the embayment has proven its versatility in recording decompression for a range of melt compositions (rhyolite: Liu et al., 2007; rhyo-dacite: Humphreys et al., 2008; basaltic-andesite: Lloyd et al., 2014; basalt: Ferguson et al., 2016), phenocryst hosts (quartz: Saalfeld et al., 2022; plagioclase: Humphreys et al., 2008; pyroxene: Myers et al., 2021; olivine: Moussallam et al., 2019), and rates ($0.0001\text{--}1\text{ MPa s}^{-1}$), and has been subjected to rigorous numerical (deGraffenried and Shea, 2021; Wei et al., 2024) and experimental (Hosseini et al., 2023) evaluation, the execution of embayment modeling using a constant-rate boundary condition has been met with variable success. In particular, some studies have been unable to model measured embayment profiles comprising multiple diffusing species (H_2O , CO_2 , S) directly from the inferred magma storage region, requiring the application of two separate constant decompression rates to best fit volatile profiles within individual embayments (e.g., Lloyd et al., 2014; Myers et al., 2018; Geshi et al., 2021). Further, some studies have applied modified (i.e., not storage) starting conditions to account for negligible CO_2 in embayments compared to co-erupted melt inclusions (e.g., Myers et al., 2018, 2021; Saalfeld et al., 2022; Elms et al., 2023; Fig. 2; Table 1). These starting conditions assume either (i) some

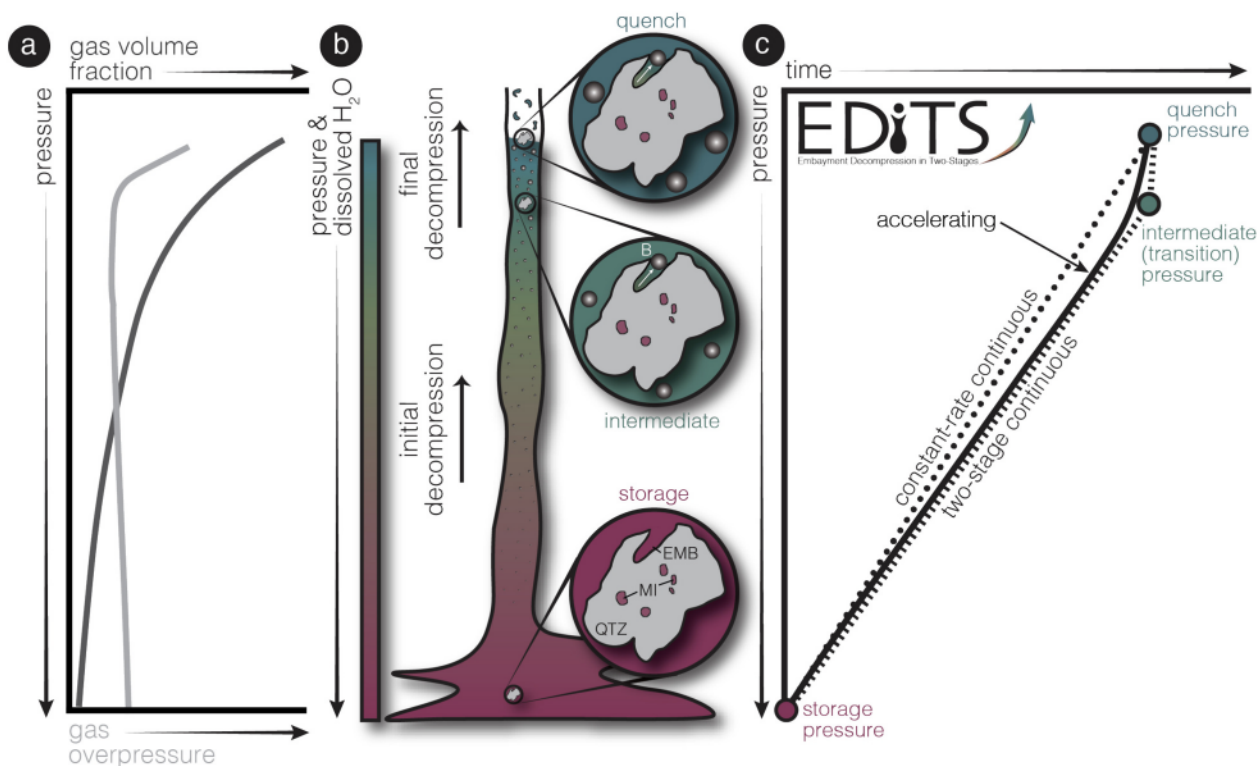


Fig. 1. (a) Illustrative model showing the evolution of gas volume fraction (dark gray curve) and overpressure (light gray curve) for a rhyolitic magma approaching the fragmentation front, modified from Gonnermann and Manga (2013). (b) Schematic of a two-stage decompression-diffusion model, where an initial slow stage of decompression allows for partial re-equilibration of the embayment melt to lower volatile concentrations prior to a faster final decompression in the upper conduit. Abbreviations are EMB – embayment, MI – melt inclusion, QTZ – quartz, and B – bubble. White arrows indicate the direction of diffusion from the interior to the outlet of the embayment. (c) Pressure-time diagram illustrating how a two-stage model (EDITS) better approximates a natural accelerating decompression path compared with a standard constant-rate, continuous decompression model.

Table 1

Compilation of embayment studies, including number of embayments analyzed, maximum melt inclusion and embayment CO₂ contents, maximum percentage of CO₂ retained in the embayment interior (compared to melt inclusion concentrations), and number of good model fits in the original studies (including percentage of total).

	Eruption	No. EMB Analyzed	Max MI CO ₂ (ppm)	Max EMB CO ₂ (ppm)	Max CO ₂ Retained (%)	No. Good Model Fits
RHYOLITIC TO DACITIC	Bandelier ^{[1]*} (1.61 and 1.26 Ma)	22	216	0	0	9 (41 %)
	Oruanui ^{[2]*} (26.5 ka)	9	200	100	50	1 (11 %)
	Huckleberry ^{[2]*} (2.08 Ma)	9	800	450	56	4 (44 %)
	Bishop ^{[2]*} (760 ka)	13	225	275		2 (15 %)
	Aira ^[3] (30 ka)	>27	250	0	0	–
	Okataina ^[4] (21.9 ka–1314 CE)	21	126	0	0	21 (100 %)
	Santorini ^[5] (3.6 ka)	11	<200	0	0	10 (91 %)
	Pinatubo ^[6] (1991)	11	<20	0	0	6 (55 %)
	Mesa Falls ^[7] (1.3 Ma)	40	669	558	83	–
	Mount St. Helens ^{[8]*} (1980)	3	–	–	–	3 (100 %)
	Fuego ^[9] (1974)	4	726	173	24	1 (25 %)
	Etna ^[10] (2013, 2015, 2018)	15	–	–	–	–
	Ambae ^[11] (2018)	10	3899	1672	43	–
BASALTIC TO ANDESITIC	Kilauea ^[12] (1500 CE, 1600 CE, 1959)	4	1200	300	25	4 (100 %)
	Seguam ^[13] (1977)	5	850	150	18	5 (100 %)

Note: all model fits based on a constant-rate modeling approach. () indicates no data collected or otherwise available. (*) indicates eruptions revisited in this study.

¹ Saalfeld et al. (2022).

² Myers et al. (2018).

³ Geshi et al. (2021).

⁴ Elms et al. (2023).

⁵ Myers et al. (2021).

⁶ Harris et al. (2024).

⁷ Befus et al. (2022).

⁸ Humphreys et al. (2008).

⁹ Lloyd et al. (2014).

¹⁰ Zuccarello et al. (2022).

¹¹ Moussallam et al. (2019).

¹² Ferguson et al. (2016).

¹³ Newcombe et al. (2020).

degree of isobaric crystallization occurred prior to eruption, driving CO₂ from the system via second boiling or (ii) exsolution of CO₂ occurred through a minor, initial decompression stage, potentially buoyancy-driven (e.g., Myers et al., 2021; Saalfeld et al., 2022) (Fig. 2). Importantly, both scenarios can produce a moderate-high H₂O and no CO₂ starting condition distinctive from the melt inclusion population. A third (iii) frequently applied ‘modified’ starting condition is the pressure associated with the maximum volatile content preserved in the embayment interior. The application of this initial condition assumes that a period of slow decompression or stalling allowed for re-equilibration of the embayment interior to a moderate H₂O and no-low CO₂ condition (e.g., Myers et al., 2018; Saalfeld et al., 2022; Elms et al., 2023) (Fig. 2). This scenario was also called upon by Lloyd et al. (2014) to explain the consistently low embayment interior CO₂ contents of Fuego embayments (<200 ppm) compared to the much wider range of co-erupted melt inclusion concentrations (100–750 ppm) (Table 1). This same observation holds across all examined eruptions, where embayment interiors retain <60 % of their initial (melt inclusion) CO₂ concentrations (the exception being the Mesa Falls Tuff; Table 1). The uncertainty in the starting volatile concentrations and corresponding pressures required to reproduce measured profiles has non-negligible effects on calculated decompression rates. Recent modeling of

embayments subjected to experimentally-controlled decompression revealed that applying shallower-than-known starting conditions yielded decompression rates up to 5× faster than the experienced rate, with equally good or better model fits (Hosseini et al., 2023). Similar results were shown numerically by deGraffenried and Shea (2021), where using the maximum H₂O content in an embayment as the starting condition, when the known value is greater, compounded errors from geometry by an additional factor of 2–10×. This finding highlights the challenges and limitations of a constant-rate modeling approach combined with uncertain starting conditions. In these cases, it is likely that magmas experienced more dynamic, multi-stage decompression histories and thus require a new modeling framework that can account for these complexities.

Here we present, validate, and apply a new MATLAB-based numerical model (Embayment Decompression in Two Stages, or EDITS) that allows for decoupling and resolution of lower and upper conduit decompression rates recorded by volatile (H₂O ± CO₂) profiles in embayments while maintaining the usability and extensibility of available constant-rate decompression models (Fig. 1b-c). This approach approximates the presumed accelerating path of magma ascent, driven by a positive feedback between decompression, volatile exsolution, buoyancy, and overpressure, with two separate stages of decompression

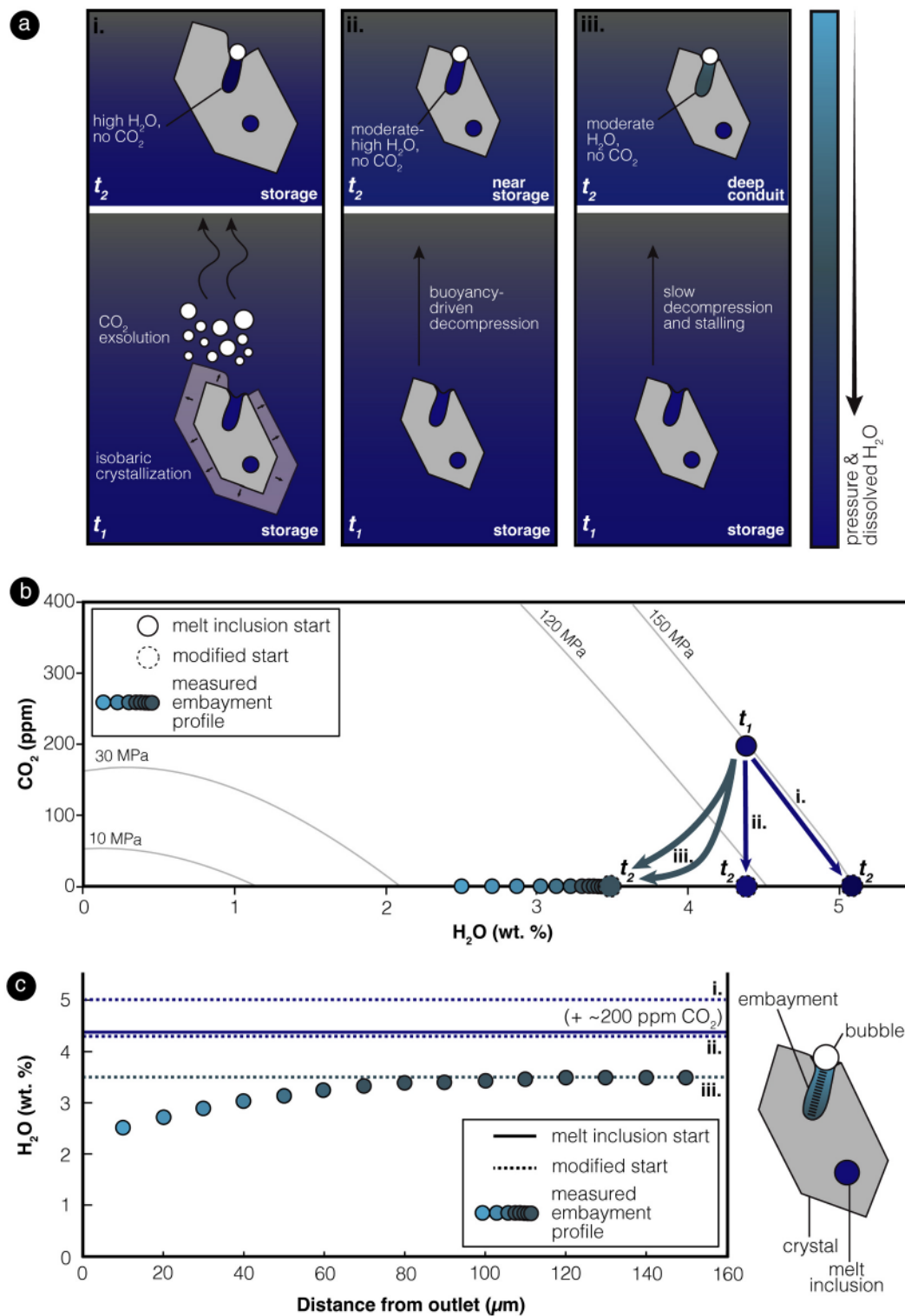


Fig. 2. Scenarios that can produce embayment $\text{H}_2\text{O} + \text{CO}_2$ contents modified (t_2) from melt inclusion (storage) concentrations (t_1), shown (a) schematically and (b-c) graphically. (i) Isobaric crystallization drives second boiling of CO_2 , resulting in low to no CO_2 in embayments despite some amount in melt inclusions. (ii) Buoyancy-driven decompression similarly results in CO_2 exsolution in a saturated system and loss from the embayment, while retaining moderate-high H_2O . (iii) A period of slow decompression or stalling during magma ascent can result in both lower H_2O in, and complete loss of CO_2 from, the embayment compared to melt inclusions. In these scenarios, applying a constant-rate model with melt inclusion starting conditions may lead to poor fits to $\text{H}_2\text{O} \pm \text{CO}_2$ gradients.

(Fig. 1b-c). Currently the code is formulated for silicic systems, from which a greater number of embayments have been measured (>80 %; Table 1) but can be modified for andesitic to basaltic systems (and the inclusion of S) using published diffusivities and solubilities (Georgeais

et al., 2021 and references therein). We first benchmark EDiTS against existing numerical embayment decompression-diffusion models, before validating it using experimentally-controlled decompression of natural quartz-hosted embayments. Finally, we apply EDiTS to existing

embayment datasets ($\text{H}_2\text{O} \pm \text{CO}_2$) from highly explosive silicic eruptions from five volcanic centers (Yellowstone, WY, USA; Valles, NM, USA; Long Valley, CA, USA; Taupo, NZ; Mount St. Helens, WA, USA) to reassess timescales of magma decompression and ascent. Through this multi-faceted approach, we aim to investigate whether (1) embayments can faithfully record, and models can be developed to extract, more complex and realistic magma decompression paths, and (2) a two-stage embayment modeling framework provides magma decompression rates in better agreement with independent estimates for historic eruptions from well-monitored volcanoes (e.g., May 18th, 1980 Mount St. Helens).

2. Model set-up and validation

2.1. Numerical model development and benchmarking

The available 1-, 2-, and 3-D models for recreating volatile diffusion profiles within embayments apply numerical (finite-difference) solutions to the diffusion equation (e.g., unnamed model (1D): Myers et al., 2018; Hosseini et al., 2023; EMBER (1D): Georgeais et al., 2021; unnamed model (1D, 3D): deGraffenried and Shea, 2021; Embayment-Diffuser (1D, 2D): Befus et al., 2022). Here, we will focus on the 1D model set-up (majority of embayment models), since a 1D solution forms the basis for EDITS. In these models, H_2O and CO_2 (e.g., Myers et al., 2018; Befus et al., 2022; Hosseini et al., 2023) and, in some cases, S (e.g., Lloyd et al., 2014; Ferguson et al., 2016; Georgeais et al., 2021; Zucarello et al., 2022) diffuse through a melt-filled embayment in response to the formation of a bubble at the channel outlet, which establishes a concentration step function between the bubble and surrounding melt. The presence of this bubble is a result of decreasing volatile solubilities and exsolution induced by magma decompression. Volatile element solubilities are well-established for a range of melt compositions and are pressure-, temperature-, and fluid composition-dependent (e.g., Newman and Lowenstern, 2002; Witham et al., 2012). Diffusivities have been experimentally determined and are pressure, temperature, H_2O -concentration and, in the case of S, oxygen fugacity dependent (Nowak and Behrens, 1997; Zhang and Behrens, 2000; Freda et al., 2003, 2005; Nowak et al., 2004; Ni and Zhang, 2008; Zhang and Ni, 2010; Zhang et al., 2010). At the crystal-melt interface, a no-flux boundary condition (Neumann boundary) is imposed, justified by the incompatibility of the diffusing volatile elements in the host crystal, such that diffusive flux is uni-directional along the length of the embayment. The boundary condition at the bubble-melt interface is updated at each decompression time-step (Dirichlet boundary), with the volatile concentration assumed to be in local equilibrium with the exsolved fluid present in the melt surrounding the crystal. We note that this assumption of an equilibrium degassing pathway is a current limitation of embayment modeling. Previous decompression experiments have shown that bubble nucleation delay and disequilibrium degassing in crystal-poor rhyolitic melts can generate significant overpressures during magma ascent (e.g., Mangan and Sisson, 2000; Cichy et al., 2011), and recent numerical studies have demonstrated the non-negligible effect of the assumed degassing mechanism on calculated embayment decompression rates (up to one order of magnitude; deGraffenried and Shea, 2021). Future embayment models would thus benefit from a greater understanding of bubble nucleation mechanisms in rhyolitic melt, as well as the development of general models describing pressure- H_2O concentration relationships during disequilibrium degassing (e.g., deGraffenried and Shea, 2021).

Model input parameters include (1) initial dissolved volatile concentration in the melt ($C_{\text{H}_2\text{O}}$, wt%; C_{CO_2} , ppm; C_{S} , ppm) which is typically determined from co-erupted melt inclusions or otherwise a 'modified' starting condition as discussed above (Fig. 2); (2) initial pressure (P_i ; MPa), which is related to volatile concentrations via solubility models (e.g., VolatileCalc, Newman and Lowenstern, 2002; MagmaSat, Ghiorso and Gualda, 2015); (3) temperature (T ; °C), which is often held constant, an assumption that is likely more appropriate in

silicic rather than basaltic systems (Mastin and Ghiorso, 2001); (4) the mass of pre-exsolved fluid; and (5) embayment length from the interior crystal-glass interface to the bubble-glass interface (x ; μm). To date, all published codes simulate a constant-rate, continuous decompression path using some or all of the above model assumptions and input parameters.

Our MATLAB-based two-stage decompression-diffusion model, EDITS, is applicable to $\text{H}_2\text{O} \pm \text{CO}_2$ diffusing through rhyolitic melt embayments, and incorporates 1D time- and concentration-dependent diffusion defined by Fick's second law:

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial x} \left(D_i \frac{\partial C_i}{\partial x} \right) \quad (1)$$

where C is the concentration of the diffusing species i in the melt (wt% or ppm), D is the diffusivity of the volatile species in silicate melt ($\mu\text{m}^2 \text{s}^{-1}$) as a function of the total dissolved H_2O concentration, x is distance (μm), and t is time (s). Solving Eq. (1) numerically requires defining appropriate initial ($t = 0$, $0 \leq x \leq L$) and boundary ($t > 0$, $x = 0$, L) conditions at the embayment outlet ($x = 0$) and interior ($x = L$), given in our model by:

$$C_{i,0 \leq x \leq L, t=0} = \text{uniform} \quad (2a)$$

$$C_{i,x=0, t>0} = C_{i,\text{solubility}} \quad (2b)$$

$$\frac{\partial C_{i,x=L}}{\partial x} = 0 \quad (2c)$$

where Eq. (2a) describes an initially uniform volatile concentration C of diffusing species i along the entire length of the embayment, Eq. (2b) defines a pressure- and time-dependent boundary condition at the bubble-melt interface (outlet) determined by the equilibrium solubility of the diffusing species i , and Eq. (2c) defines a no-flux boundary condition at the melt-crystal interface (interior). EDITS incorporates the empirical expressions of Liu et al. (2005) to model H_2O and CO_2 solubility (see Eqs. 2a and 2b in Liu et al., 2005). For H_2O and CO_2 diffusivities, we use equations given by Zhang and Behrens (2000), applicable to a wide range of conditions (400–1200 °C, 0.1–810 MPa, and 0.1–7.7 wt% total H_2O), and Zhang et al. (2007), respectively.

The code and all relevant documentation are available on GitHub and archived on Zenodo (<https://zenodo.org/record/10042159>). EDITS expands on the models of Myers et al. (2018) and Hosseini et al. (2023) by implementing a new free parameter iteration structure. The original model cycles through a range of unknown inputs including initial exsolved fluid content (r ; wt%), decompression rate (dP/dt ; MPa s^{-1}), and fragmentation pressure (P_f ; MPa), where diffusion ceases due to rapid quenching of embayment melt. A χ^2 misfit is calculated based on the difference between the measured and modeled profiles with this value determined iteratively for every combination of parameters:

$$\chi^2 = \sum_{x=1}^L \frac{C_{i,x,\text{measured}} - C_{i,x,\text{modeled}}}{\sigma_{i,x}^2} \quad (3)$$

Where $C_{i,x,\text{measured}}$ is the measured concentration of volatile species i at position x in the compositional profile, $C_{i,x,\text{modeled}}$ is the modeled volatile concentration, and $\sigma_{i,x}$ is the uncertainty of the measured concentration. The best-fit profile is determined by the combination of parameters that minimizes χ^2 (Eq. 3) for fitting H_2O and CO_2 simultaneously. Here, we apply the same misfit calculation but instead cycle through the following three user-defined, incremented parameters: initial (deeper; dP/dt_i) and final (shallower; dP/dt_f) decompression rates, as well as the pressure where this transition occurs (P_t). In this framework, the code now consists of two constant-rate, continuous decompression stages where, at a given transition pressure, the $\text{H}_2\text{O} \pm \text{CO}_2$ diffusion profiles produced during the first (initial) stage of decompression are used as inputs (starting conditions) for the second (final) stage of decompression. The tradeoff of this model set-up is that initial exsolved gas content and

quench pressure are no longer free model parameters and thus need to be estimated independently. For example, the quench pressure can be determined from the $\text{H}_2\text{O} \pm \text{CO}_2$ concentration near the embayment outlet or adhering matrix glass (e.g., Lloyd et al., 2014), and the exsolved gas content can be estimated using other embayment models (e.g., Myers et al., 2013). Fig. A1 provides a graphical flow-chart summary of the code architecture.

While there are no independent two-stage models to benchmark EDiTS against, we are able to validate our code by using constant-rate, continuous models to produce synthetic H_2O and CO_2 concentration profiles characterized by known deeper and shallower decompression rates (Fig. A2). Using the code of Hosseini et al. (2023), we first modeled an initial decompression stage (dP/dt_i) from 150 MPa (3 wt% H_2O and ~680 ppm CO_2) to an intermediate pressure (P_t ; 100, 90, or 80 MPa) at a specific rate (0.001, 0.005, or 0.009 MPa s^{-1}). The resulting H_2O and CO_2 concentration profiles from this initial stage were then used as the starting conditions for the final decompression stage (dP/dt_f) from the intermediate pressure to the quench pressure (P_f ; 30, 15, or 10 MPa) at a specific rate (0.01, 0.05, or 0.09 MPa s^{-1}). The resulting ‘synthetic’ profiles were input as ‘measured’ $\text{H}_2\text{O} + \text{CO}_2$ profiles for recreation by EDiTS. For the three distinct synthetic profiles that were produced using different initial and final decompression rates and transition pressures, we were able to successfully extract the known decompression paths with χ^2 misfits of 0 using EDiTS (Fig. A2; Table 2). This is an expected result since both models use the same parameterizations, but nevertheless demonstrates that the two-stage code is performing in the intended manner. We are confident that tests using synthetic volatile profiles generated by other 1D models should lead to similarly low χ^2 misfits in EDiTS, with any divergence resulting from the volatile solubility and diffusivity equations defined within each model.

We also test how EDiTS performs in recreating synthetic H_2O and CO_2 profiles produced by a single stage, constant-rate decompression. Here we find that the model can recover initial and final rates that bracket the experienced constant rate (i.e., a false positive result) (Table 2). For instance, for synthetic $\text{H}_2\text{O} + \text{CO}_2$ profiles produced by a constant decompression rate of 0.008 MPa s^{-1} from 150 to 30 MPa, EDiTS recovers a best-fit initial decompression rate of 0.004 MPa s^{-1} from 150 to 80 MPa, and 0.01 MPa s^{-1} from 80 to 30 MPa. We discuss the implications of this result later.

2.2. High pressure-temperature decompression experiments

Our second validation approach is to apply EDiTS to model embayment profiles produced during two-stage, mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) and pure H_2O -saturated decompression experiments. Hosseini et al. (2023) present a method to successfully re-equilibrate natural quartz-hosted embayments to new starting pressures and fluid compositions using a rapid-quench cold-seal pressure vessel at the University of Oregon. Each experimental charge consists of Bishop ash (<60 μm)

doped with 10 wt% oxalic acid dihydrate (OAD), natural quartz crystals with embayments, and nickel-nickel oxide (NNO) buffer. The embayment melt is re-equilibrated at high pressures (150 MPa) and temperatures (780 °C), where the OAD breaks down to form an H_2O - CO_2 fluid mixture. The charge is then subjected to controlled, constant-rate, continuous decompression. Embayments record volatile diffusion profiles characterized by known decompression rates that were able to be successfully recovered via numerical diffusion modeling. Following the methodology outlined in Hosseini et al. (2023), we further develop the technique by conducting multi-stage, continuous decompression experiments, with the goal of testing the ability of EDiTS to recover known two-stage decompression paths and transition pressures from re-equilibrated natural embayments (Fig. A3; Table A1). One H_2O -saturated experiment (E4-2) was conducted in which we decompressed the charge from 150 MPa at an initial rate of 0.006 MPa s^{-1} before transitioning at 100 MPa to 0.02 MPa s^{-1} and air quenching at 30 MPa (total decompression time 3.28 h; Fig. 3; Fig. A3; Table A1). In the mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) saturated experiment (E3-2), we decompressed the charge from 150 MPa at 0.009 MPa s^{-1} before ramping up, at 80 MPa, to 0.06 MPa s^{-1} and air quenching at 30 MPa (total decompression time 2.39 h; Fig. 4; Fig. A3; Table A1). We additionally conducted one stalling experiment in which the charge was decompressed from 150 MPa to 80 MPa at a constant rate of 0.02 MPa s^{-1} , stalled for three hours, and then decompressed at the same constant rate until quench at 30 MPa (total decompression time 1.66 h, total experiment time 4.66 h; Fig. A3; Table A1). Three glassy embayments recovered from these experiments (one from each) were prepared for analyses of $\text{H}_2\text{O} \pm \text{CO}_2$ transects using a Nicolet iN10 infrared microscope and integrated spectrometer at Montana State University. The embayment from the H_2O -saturated experiment preserves a gradient from ~2.5 wt% H_2O at the outlet that plateaus at ~3.5 wt% H_2O at the interior (Fig. 3; Table A2). Lower H_2O (2–3 wt%) characterizes the gradient in the embayment from the mixed-volatile experiment, with CO_2 ranging from 175 to 250 ppm (Fig. 4; Table A2). The stalled embayment preserves a H_2O gradient from 1 to 1.9 wt% with CO_2 ranging from 35 to 175 ppm (Table A2). Full experimental set-up and procedures, along with FTIR spectroscopy data collection and processing, are outlined in Hosseini et al. (2023) and provided in the Supplementary Material (Text A1-A2, Tables A1-A2, Fig. A3).

We applied EDiTS to assess how accurately the known experimental decompression paths could be extracted from preserved embayment $\text{H}_2\text{O} \pm \text{CO}_2$ concentration gradients, allowing dP/dt_i , dP/dt_f , and P_t to vary freely. Modeling the three recovered embayments from two-stage experiments, one from a continuously decompressed H_2O -saturated experiment (E4-2), one from a continuously decompressed mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) experiment (E3-2), and the final from a stalled mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) experiment (E1-2), we note some significant observations. For the H_2O -saturated experiment (E4-2), we recover equally good fits to the H_2O gradient using the constant-rate (0.011 MPa

Table 2

Summary of results from applying constant-rate (Hosseini et al., 2023) and two-stage (EDiTS) models to experimental and synthetic $\text{H}_2\text{O} \pm \text{CO}_2$ profiles. ‘True positive’ results occur when a given model recovers known synthetic or experimental decompression conditions. ‘False positive’ results occur when a given model recovers non-experienced synthetic or experimental decompression conditions.

		Model	
		Constant-rate (Hosseini et al., 2023)	Two-stage (EDiTS)
Experimental	Constant rate	Validated by Hosseini et al. (2023) for both H_2O -only and $\text{H}_2\text{O} + \text{CO}_2$ profiles.	This study. Can produce a false positive result for both H_2O -only and $\text{H}_2\text{O} + \text{CO}_2$ profiles.
	Two-stage	This study. Cannot simultaneously fit $\text{H}_2\text{O} + \text{CO}_2$ profiles. Can produce a false positive fit to a H_2O -only profile.	This study. Can successfully fit $\text{H}_2\text{O} + \text{CO}_2$ profiles with known dP/dt_i , P_t , and dP/dt_f . No unique fit to H_2O -only profiles.
Synthetic	Constant rate	Perfect fits, N/A.	This study. Can produce a false positive result, where dP/dt_i , P_t , and dP/dt_f are recovered with a misfit of 0.
	Two-stage	This study. Can produce a false positive fit to both H_2O -only and $\text{H}_2\text{O} + \text{CO}_2$ profiles that roughly averages the decompression path.	This study. Can successfully recover dP/dt_i , P_t , and dP/dt_f with a misfit of 0.

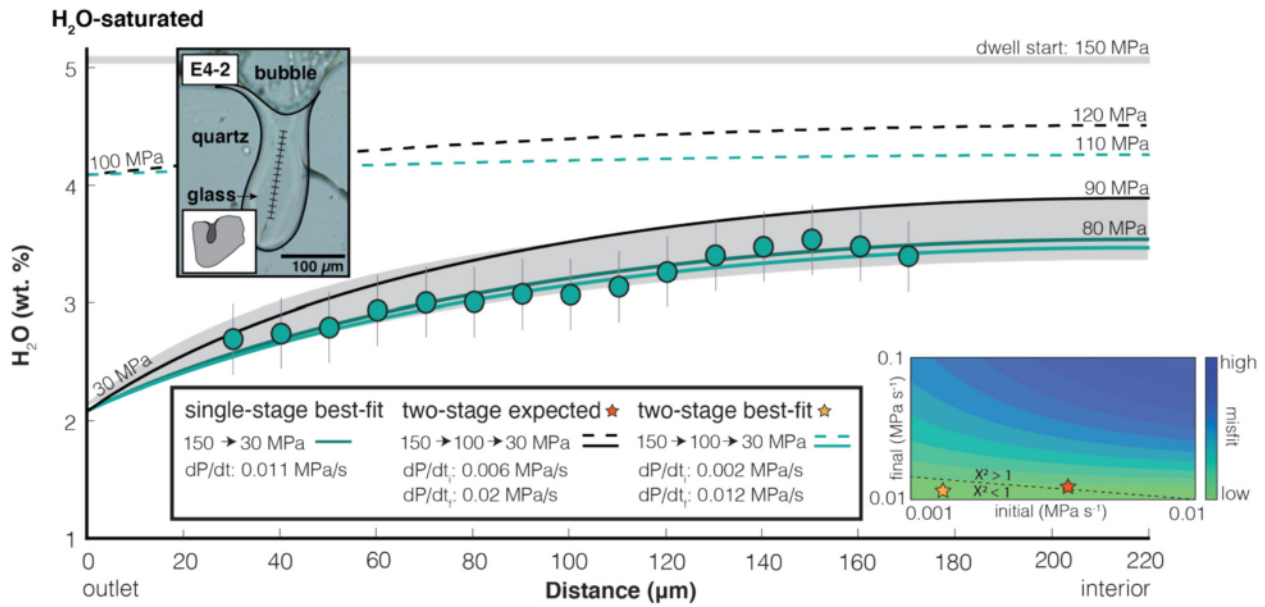


Fig. 3. Modeling results for embayment E4-2, shown in transmitted light in the upper left and annotated with the measured transect, with inset showing a cartoon rendering of the host crystal for context. E4-2 was recovered from a H₂O-saturated experiment that decompressed from 150 to 100 MPa at 0.006 MPa s⁻¹, and from 100 to 30 MPa at 0.02 MPa s⁻¹. Horizontal gray bar denotes the starting condition used to model this embayment (5.1 wt% H₂O), determined by an H₂O-saturated equilibrium (dwelt) experiment conducted by Hosseini et al. (2023) at 780 °C and 150 MPa. Measured transect shown as teal circles. Black curves indicate the expected profile and light teal curves the recovered best-fit profile, both for the initial stage (dashed) and the final stage (solid) of decompression. Also shown is the best-fit profile using the constant-rate model of Hosseini et al. (2023) (dark teal curve). Shaded gray curved region signifies the range of good model fits to the measured profile at a fixed transition pressure (100 MPa). Analytical error shown as light gray vertical bars on measured points. Lower right χ² misfit contour plot illustrates the range of initial decompression rates (x-axis) at a fixed transition pressure (100 MPa) that produce good model fits, compared to much more constrained final rates (y-axis). The misfits for the expected (orange star) and recovered (yellow star) model fits are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

s⁻¹; χ² = 0.09) and two-stage (0.002 → 0.012 MPa s⁻¹; χ² = 0.08) models (Fig. 3; Table 2). This highlights the previously-recognized challenge of discerning unique embayment decompression paths using only a single diffusing volatile specie (e.g., Lloyd et al., 2014; Hosseini et al., 2023). We also observe that the constant-rate model recovers a best-fit decompression rate that roughly averages the two-stage decompression path, confirming that a constant-rate modeling approach can blur the effects of acceleration or multi-stage ascent histories. Translating these recovered decompression rates to ascent time via:

$$t_{\text{constant}} = \frac{P_i - P_f}{dP/dt} \quad (4a)$$

$$t_{\text{two stage}} = \frac{P_i - P_t}{dP/dt_i} + \frac{P_t - P_f}{dP/dt_f} \quad (4b)$$

where P_i , P_t , and P_f are the initial, transition, and final pressures and dP/dt is the decompression rate, we find that the constant-rate model (3.03 h) closely approximates the known total ascent time (i.e., experiment duration, 3.28 h), while the two-stage model (8.56 h) poorly approximates the known ascent time. However, the two-stage model reasonably approximates the final, rapid stage of decompression from 100 to 30 MPa (97.2 mins recovered vs. 58.3 mins known), while this time cannot be resolved using the constant-rate model. While a wide range of initial decompression rates can fit the measured profile (0.001–0.009 MPa s⁻¹ translating to 1.5–13 h of ascent time), the final stage of decompression is much more constrained (good fits between 0.01 and 0.02 MPa s⁻¹ equating to 1.94 h–58 mins of ascent time). Overall, these results highlight that most of the error in recovering the experienced path from H₂O profiles results from the poor constraints on the initial, slower stage of decompression, where in this case EDITS recovers an initial ascent time (6.9 h) a factor of three greater than that

experienced (2.3 h) (Fig. 3).

Conversely, for the continuously-decompressed two-stage mixed-volatile experiment (E3-2), we are only able to fit the H₂O and CO₂ embayment profiles simultaneously using EDITS (Fig. 4). For this embayment, the constant-rate model recovers a best fit decompression rate (characterized by an unacceptable fit to the CO₂ profile) of 0.025 MPa s⁻¹, with a recovered ascent time (1.33 h) that underestimates the experienced time (2.39 h). This code again recovers a decompression rate that averages the known initial (0.009 MPa s⁻¹) and final (0.06 MPa s⁻¹) stages. On the other hand, the two-stage model recovers an initial rate of 0.008 MPa s⁻¹ (0.009 MPa s⁻¹ expected) that transitions at 80 MPa (the imposed transition pressure) to 0.1 MPa s⁻¹ (0.06 MPa s⁻¹ expected; Fig. 4). This translates to a total ascent time of 2.57 h recovered by the two-stage model, in close agreement with the known decompression duration (2.39 h), as well as a very well-constrained final stage of decompression (8.3 mins recovered vs. 13.8 mins expected). These results suggest that modeling multiple diffusing species simultaneously provides crucial constraints for resolving the true decompression path, and more significantly, that a mixed-volatile system that has experienced multi-stage or accelerating magma decompression may not be successfully modeled using a constant-rate approach with 'melt inclusion' starting conditions (Fig. 4). Finally, in applying the constant-rate model of Hosseini et al. (2023), as well as EDITS, to the stalled embayment (E1-2), we are unable to simultaneously fit H₂O and CO₂ concentration gradients. This optimistically suggests that neither constant-rate nor two-stage models may reproduce embayment volatile profiles generated by more complex scenarios, such as hours of crustal stalling.

A final important observation is that the saturation pressure preserved in the interior of each of the two continuously-decompressed (i.e., not stalled) experimental embayments (3.55 wt% H₂O = 80 MPa for E4-2 and 3.16 wt% H₂O + 264 ppm CO₂ = 110 MPa for E3-2; calculated using the solubility model of Liu et al. (2005) in VESICAL: Iacovino et al.,

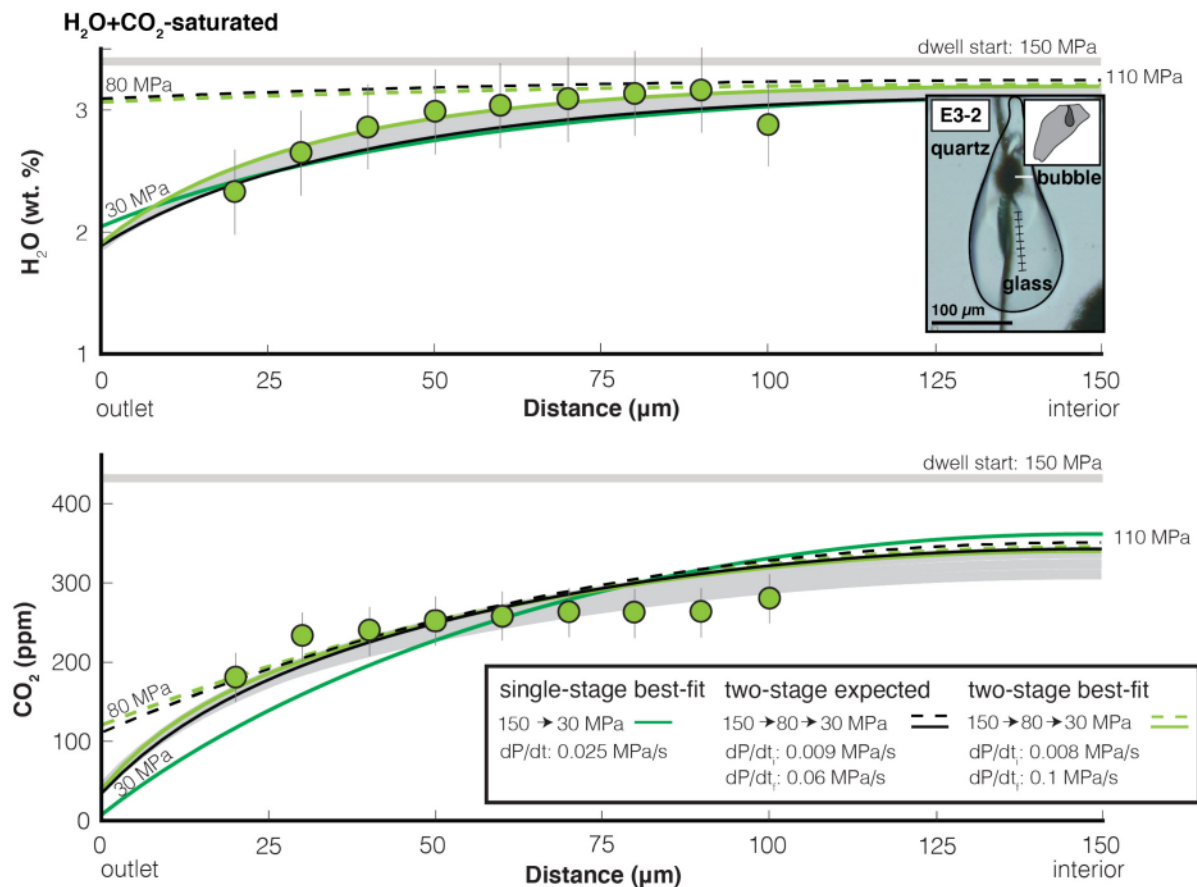


Fig. 4. Modeling results for embayment E3-2, shown in transmitted light in the upper right and annotated with the measured transect, with inset showing a cartoon rendering of the host crystal for context. E3-2 was recovered from a mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$)-saturated experiment that decompressed from 150 to 80 MPa at 0.009 MPa s^{-1} , and from 80 to 30 MPa at 0.06 MPa s^{-1} . Horizontal gray bars on upper (H_2O) and lower (CO_2) plots denote the starting conditions used to model this embayment (3.4 wt% H_2O and 425 ppm CO_2), as determined by the mixed-volatile saturated dwell experiments of Hosseini et al. (2023), conducted at 780°C and 150 MPa. Measured transects shown as green circles. Black curves indicate the expected profile, and light green curves the recovered best-fit profile, both for the initial (dashed) and final (solid) stages of decompression. Also shown is the best-fit profile using the constant-rate model of Hosseini et al. (2023) (dark green curve). Shaded gray curved region signifies the range of good model fits to the measured profile at a fixed transition pressure (80 MPa). Analytical error shown as light gray vertical bars on measured points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2021) is within ~ 20 – 30 MPa of the transition pressure imposed in the experiment (Figs. 3 and 4). Although this is not necessarily a surprising result, as the increased final decompression rate will provide less time for interior relaxation to occur, it does provide some useful constraints on model input parameters. We therefore suggest that when applying EDiTS to natural embayments the user should use the saturation pressure preserved in the embayment interior plateau to inform the range of transition pressures cycled through during a model run. This will also help reduce the model run time and convergence on a best-fit solution, since there is a significant tradeoff between initial decompression rate and transition pressure which results in many equally good fits to the measured profiles.

To again test the result of applying a multi-stage decompression code to an embayment that experienced a known constant-rate path, we applied EDiTS to a subset of embayments from the pure H_2O - and mixed-volatile ($\text{H}_2\text{O} + \text{CO}_2$) saturated, constant-rate experiments presented in Hosseini et al. (2023). The H_2O -saturated experiment (E8-1) was decompressed from 150 to 30 MPa at 0.015 MPa s^{-1} and the $\text{H}_2\text{O} + \text{CO}_2$ experiment (E3-1) decompressed from 150 to 30 MPa at 0.008 MPa s^{-1} . For embayment E8-1, EDiTS recovers a best-fit profile characterized by an initial decompression rate of 0.004 MPa s^{-1} that transitions at 60 MPa to 0.015 MPa s^{-1} . Although the recovered final stage of decompression equals the imposed rate (0.015 MPa s^{-1}), the initial slow stage adds several hours to the total ascent time (e.g., ~ 6.5 h recovered vs. 2.2 h imposed) while maintaining a similarly low misfit ($\chi^2 = 0.02$ for two-

stage vs. 0.03 for constant-rate). We find a similar result for embayment E3-1 from the mixed-volatile experiment; while EDiTS recovers a best-fit profile defined by an initial decompression rate of 0.007 MPa s^{-1} that transitions at 50 MPa to 0.01 MPa s^{-1} (~ 4.5 h of ascent time), the experienced constant decompression rate was 0.008 MPa s^{-1} from 150 to 30 MPa (~ 4.2 h of ascent time). Thus, similar to the synthetic test results, we find that in both H_2O -only and mixed-volatile systems, EDiTS can produce a false positive result, meaning a best-fit diffusion profile characterized by two stages of decompression can be recovered even when the embayment experienced a constant rate of decompression (Table 2). We argue, however, that this result is a red herring and does not have any bearing on the application of EDiTS to natural systems, since most natural magmas are unlikely to experience a constant, linear decompression history from storage to fragmentation.

3. Model application

3.1. Revisiting existing embayment studies

To date, there have been 14 embayment studies published on rhyolitic to basaltic systems, representing 27 eruptions (14 pre-historic and 13 historic) and including over 200 embayments (Table 1). Below, we present results from applying EDiTS to a subset of previously modeled embayments ($n = 5$), reevaluating four pre-historic eruptions (all caldera-forming, rhyolitic; Table 3), as well as reassessing the

Table 3
Results from remodeling embayments from four silicic caldera-forming (Huckleberry, Bishop, Oruanui) and one arc (May 18th, 1980 Mount St. Helens) eruption using EDITS, and comparison with original constant-rate modeling results from: [†] Myers et al. (2018), [‡] Saalfeld et al. (2022), and [o] Humphreys et al. (2008). (-) indicates that CO₂ was not measured in the original study, and χ^2 misfits were not reported.

Eruption	Sample	Constant-rate model					Two-stage model (EDITS)										
		Starting pressure (MPa)	H ₂ O (wt%)	CO ₂ (ppm)	Decompression rate (MPa s ⁻¹)	Quench pressure (MPa)	Ascent rate (m s ⁻¹)	Ascent time (mins)	χ^2	Decompression rate (initial) (MPa s ⁻¹)	Decompression rate (final) (MPa s ⁻¹)	Transition pressure (MPa)	Ascent rate (initial) (m s ⁻¹)	Ascent rate (final) (m s ⁻¹)	Ascent time (initial) (min)	Ascent time (final) (min)	χ^2
Huckleberry [†]	MM7 RE no. 10	150	4.1	325	0.027	17	1.06	82.2	0.20	0.002	0.063	70	0.08	2.47	680	13.8	0.75
Bandelier [†]	T1-3	162	5.5	57	0.005	15	0.18	500	0.33	0.004	0.1	20	0.16	1.95	592	1.8	0.08
	T2-3	121	4.5	117	0.007	30	0.28	215	4.22	0.001	0.037	80	0.04	1.45	677	19.2	0.55
Bishop [†]	BTP9_138 RE no. 2	220	5.4	475	0.042	30	1.53	83.4	0.9	0.005	0.06	155	0.20	2.35	217	43	0.68
Oruanui [†]	P1970-A RE no. 6	190	5.0	325	0.017	45	0.67	142.2	0.34	0.005	0.08	75	0.20	3.14	383	6	0.48
MSH ^o	KVC518b	230	6.4	-	1.4	33	54.89	2.4	-	0.009	0.76	60	0.35	29.80	392	0.6	0.9
MSH ^o	MSH1-3	230	6.4	-	1.6	27	62.73	2.4	-	0.01	0.23	100	0.39	9.02	287	5.4	4.1
MSH ^o	MSH1-6	230	6.4	-	1.3	9	50.97	3	-	0.008	0.65	90	0.31	25.48	379	1.8	4.8

embayments ($n = 3$) from the closely monitored and well-documented May 18th, 1980 eruption of Mount St. Helens (rhyo-dacitic) (Table 3; Fig. 5). To allow for comparability of EDITS results with those presented in the original constant-rate modeling studies, we use the same starting H₂O $\pm$ CO₂ and corresponding pressures, quench pressures, and exsolved gas contents as the original studies.

3.1.1. Applications to pre-historic eruptions

The majority of embayments from pre-historic caldera-forming eruptions have lacked measurable CO₂, although co-erupted melt inclusions often contain a moderate amount (Table 1). The sparsity of CO₂ in embayments from many eruptions (e.g., Bandelier, NM, USA; Bishop, CA, USA; Oruanui, NZ) has been interpreted to result from one or both of the following scenarios: either CO₂ was driven out of the system prior to eruption due to isobaric crystallization (e.g., second boiling), or the system experienced an initial slow stage of ascent prior to eruption permitting CO₂ re-equilibration (Myers et al., 2018, 2021; Saalfeld et al., 2022). We applied EDITS to these systems to test previously presented ideas, allowing for melt inclusion H₂O $\pm$ CO₂ concentrations to be used as starting conditions. We remodeled measured volatile gradients from five select embayments from four caldera systems (Yellowstone, WY; Valles, NM; Long Valley, CA; Taupo, NZ), targeting samples with both H₂O and CO₂ gradients present, when possible, for better modeling constraints (Table 3). We find that for all systems, volatile gradients are best fit with an initial deeper decompression stage equivalent to 3.5–11 h, a final shallower stage equivalent to hours to 10s of minutes, and transition pressures (70–155 MPa) that agree closely with embayment interior pressures (Table 3). This lends credence to the idea that for eruptions with CO₂-bearing melt inclusions, embayments with low-no CO₂ could be a record of longer (>10 h) initial decompression, allowing partial to full re-equilibration to occur, as was suggested for 1974 eruption of Fuego (Lloyd et al., 2014), the Late Bronze Age eruption of Santorini (Myers et al., 2021), and the 1.6 and 1.2 Ma eruptions of the Bandelier Tuff (Saalfeld et al., 2022). Further, our two-stage model may better constrain the final, explosive stage of each eruption, providing times on the order of 10s of minutes, where the constant-rate model produces total ascent times on the order of hours. However, because pre-historic eruptions lack independent, real-time constraints on magma ascent rates, we are limited in terms of how we interpret and validate the EDITS results, and so, as a case study, we turn our assessment to a modern, instrumented eruption that includes both independent petrologic (e.g., bubble number densities) and real-time observational decompression rate estimates: the May 18th, 1980 Plinian eruption of Mount St. Helens.

3.1.2. Applications to historic instrumented eruptions

Integrating petrologic records with real-time observations of magma ascent and eruption remains a great ambition of volcano science (e.g., Rasmussen et al., 2018; Ruth et al., 2018; Caricchi et al., 2021). While the fidelity of embayments to record magma decompression has been well-established (e.g., Hosseini et al., 2023), the recovered rates have largely remained decoupled from independent records (e.g., Fig. 6a). We argue that this discordance between different decompression rate estimates is in part an artifact of the model framework. We next demonstrate the ability of EDITS to reconcile embayment- and monitoring-based magma ascent rates, as applied to the 1980 Plinian eruption of Mount St. Helens (Washington, USA). On May 18th, 1980 at 0832 PDT, a magnitude 5 earthquake triggered the failure of the north flank leading to, in sequence, a debris avalanche, lateral blast, and eruptive column (Voight et al., 1981; Kieffer, 1981; Eichelberger and Hayes, 1982). Sustained Plinian activity continued for nine hours, with the eruption column reaching a mean height of 16 km (Carey and Sigurdsson, 1985; Carey et al., 1990). The record of strong ground shaking for the May 18th eruption reveals two distinct phases of activity, where the first coincides with the M5 earthquake, landslide, and lateral blast, lasting ~15 min (Scandone and Malone, 1985). The onset of the second phase

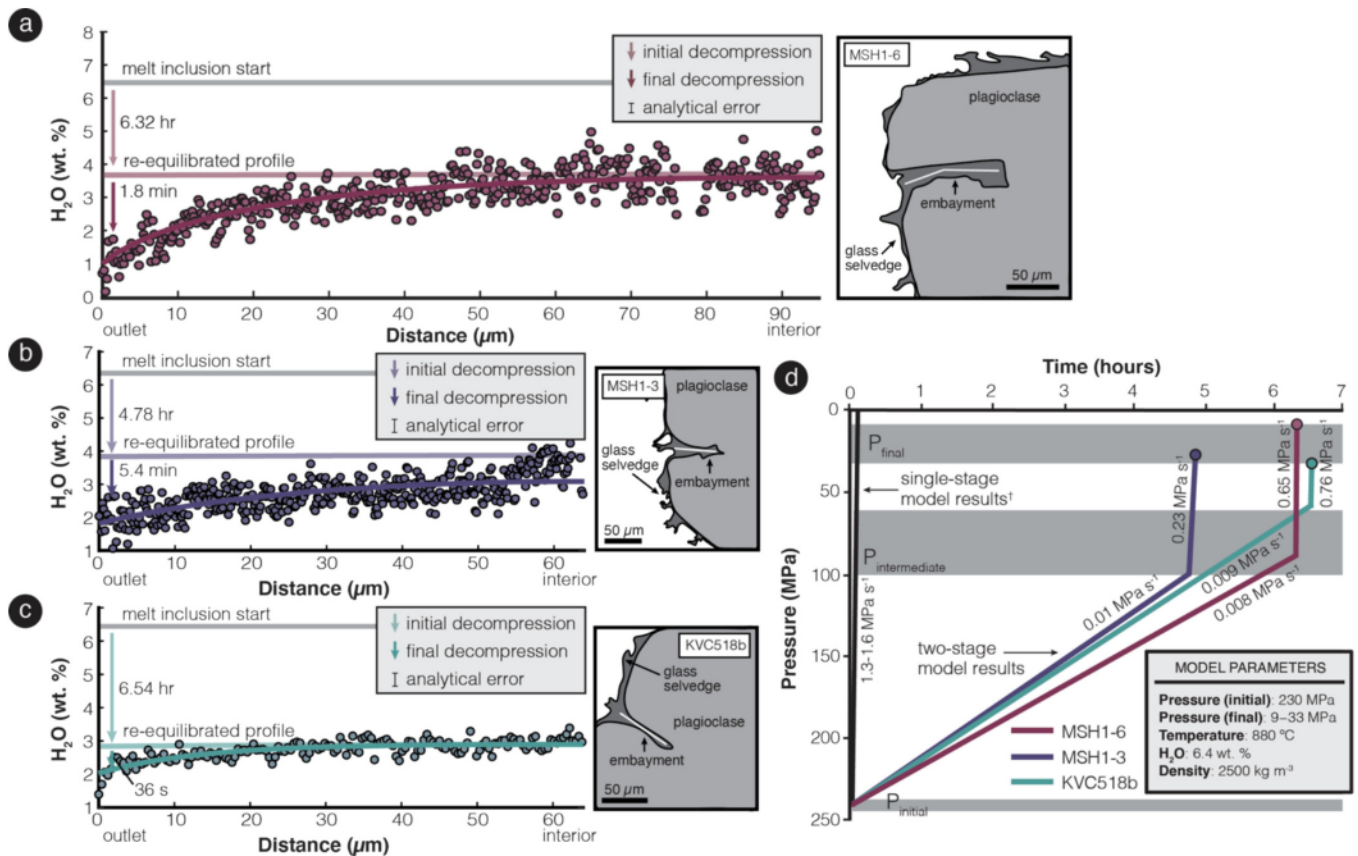


Fig. 5. EDITS applied to embayments (a) MSH1-6, (b) MSH1-3, and (c) KVC518b of Humphreys et al. (2008). Using the same high melt inclusion starting condition (6.4 wt%, gray horizontal bar), the two-stage model recovers an initial stage of decompression spanning 4.78–6.54 h (light arrow and horizontal bar), and a final stage <1–5 min (dark arrow and curve), whereas the original estimate was 2.4–3 min of total ascent time. The cartoon to the right of each panel (a–c) shows the plagioclase crystal containing the analyzed embayment, along with the annotated grayscale transect (white lines). All grayscale transect data plotted in (a–c) are sourced from Humphreys et al. (2008). (d) Pressure-time plot comparing results from the single-stage model of Humphreys et al. (2008)[†] (1.3–1.6 MPa s^{−1}) and EDITS applied to the same suite of Mount St. Helens embayments. EDITS recovers consistent initial ascent rates ranging from 0.31 to 0.39 m s^{−1}, with final ascent rates up to two orders of magnitude faster (9–30 m s^{−1}). Horizontal gray bars represent the range of P_{initial} , $P_{\text{intermediate}}$, and P_{final} used for modeling MSH embayments. $P_{\text{intermediate}}$ is a free parameter in the model, and should be controlled dynamically by where H₂O begins to rapidly exsolve. Model input parameters are shown in the lower right of the plot, including a starting pressure of 230 MPa, final pressures between 9 and 33 MPa, an isothermal temperature of 880 °C, initial H₂O of 6.4 wt%, and melt density of 2500 kg m^{−3}.

manifested as strong ground motion accompanied by an eruptive column ~3.5 h after the lateral blast; this was used to calculate magma ascent on the order of 0.6–0.7 m s^{−1} from 7 to 9 km depth (Fig. 6; Scandone and Malone, 1985; Eichelberger, 1995). This sequence has been interpreted as the eruption of a shallow magmatic body (lateral blast) that triggered the ascent of deep, volatile-rich magma (Plinian phase). Currently there is an orders-of-magnitude discrepancy between the rapid embayment-based decompression rates (1.3–1.6 MPa s^{−1} assuming $C_{\text{H}_2\text{O}} = 6.4$ wt% and 0.9–1.2 MPa s^{−1} assuming $C_{\text{H}_2\text{O}} = 4.6$ wt%) presented by Humphreys et al. (2008) using a constant-rate model, and those estimated by independent real-time observations and seismicity (0.01–0.02 MPa s^{−1}; Endo et al., 1981; Scandone and Malone, 1985; Eichelberger, 1995) (Fig. 6a). We apply EDITS to remodel grayscale-calibrated H₂O concentration gradients in these plagioclase-hosted embayments ($n = 3$) from the Plinian (May 18th) phase of the eruption (Humphreys et al., 2008), allowing for the incorporation of an initial deeper stage of decompression (Table 3; Fig. 5).

Assuming the same input parameters presented by Humphreys et al. (2008) and derived from Blundy and Cashman (2005) and Blundy et al. (2006) (i.e., $C_{\text{H}_2\text{O}} = 6.4$ wt% H₂O, $P_i = 230$ MPa, $T = 880$ °C), EDITS recovers best fit profiles characterized by an initial slow decompression (0.008–0.01 MPa s^{−1}) followed by a final stage up to two orders of magnitude faster (0.2–0.8 MPa s^{−1}). Combined with recovered transition pressures (60–100 MPa, 2.4–4 km), initial ascent rates and times

range from 0.3 to 0.4 m s^{−1} and 4.8–6.5 h, respectively, with final ascent rates of 9–30 m s^{−1} translating to <1–5 min in the shallow conduit (Fig. 5). These final rates are significantly faster than those determined for the larger caldera forming eruptions above, but are in agreement with numerical conduit model predictions (e.g., Mastin, 2005). More importantly, our results bring petrologic estimates of magma ascent into closer agreement with the monitoring record by supporting the presence of an initial slower stage of magma decompression on the order of hours, where previously the total embayment-derived ascent time was 2.4–3 min (Fig. 6). We additionally find reconciliation between the final decompression rates recorded by the embayment population (0.2–0.8 MPa s^{−1}) and updated bubble number density estimates based on time-integrated, heterogeneous bubble nucleation models (0.8 MPa s^{−1}; Hajimirza et al., 2021; Fig. 6b). Although based on a limited dataset, these results give confidence that embayments, when combined with appropriate diffusion models, can provide valuable and complementary insights into the rates of magma ascent for historic, well-monitored and instrumented eruptions.

4. Broad implications

Our combined numerical and experimental results suggest that the melt embayment can record, and models can be developed to recover, multi-stage decompression histories that provide crucial insights into

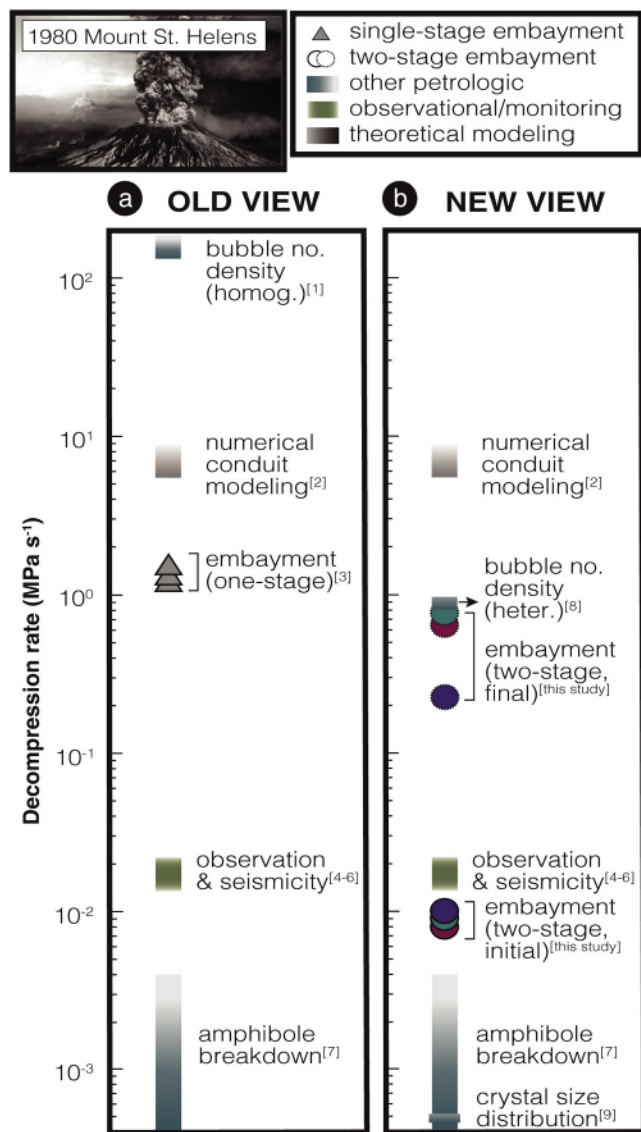


Fig. 6. Compilation of magma decompression rates for the May 18th, 1980 Plinian eruption of Mount St. Helens, based on petrological, observational, and numerical approaches. (a) In the “Old View,” magma decompression rate estimates span five orders of magnitude between different petrologic recorders, with no overlap between any approach. Further, we find no agreement between petrologic estimates and other independent, direct observations. (b) Notably EDiTS brings embayment-based ascent time estimates (4.8–6.5 h) into closer agreement with observational data, which indicate the onset of the second Plinian explosive pulse occurred 3.5 h following the unroofing of the system due to an earthquake-triggered landslide and blast. Additionally, application of new models incorporating time-integrated, heterogeneous bubble nucleation into models of vesicle number densities lower original estimates by two orders of magnitude, in good agreement with the final rapid stage of decompression recovered from embayments using our two-stage model (Hajimirza et al., 2021). Data sources are as follows: [1] Toramaru (2006), [2] Carey and Sigurdsson (1985), [3] Humphreys et al. (2008), [4] Endo et al. (1981), [5] Scandone and Malone (1985), [6] Eichelberger (1995), [7] Rutherford and Hill (1993), [8] Hajimirza et al. (2021) and [9] Andrews and Befus (2020).

how quickly magma ascends to the surface during explosive volcanic eruptions. Applying EDiTS to $H_2O + CO_2$ profiles in embayments from both pre-historic and modern eruptions provides consistent results that magma ascent from the storage region and through the deeper conduit can be quite slow, with the shallower conduit characterized by faster ascent times on the order of an hour to minutes. For the May 18th, 1980

eruption of Mount St. Helens, we find that EDiTS more effectively resolves the time of initial decompression in the deep conduit, which pairs well with independent estimates of magma ascent (e.g., direct observations and seismicity). Final decompression in the shallow conduit occurs on the order of minutes and is in close agreement with time-integrated bubble number density decompression estimates, as was similarly shown for the 1991 eruption of Mount Pinatubo (Hajimirza et al., 2021; Harris et al., 2024). We argue that the embayment is the only petrologic tool from which we are currently able to recover multiple decompression rates representative of a single magma's decompression path along different regions of the conduit. Previous studies have presented evidence that initial magma ascent can be aseismic (i.e., too slow to produce detectable seismicity), as was the case for the 2009 eruption of Redoubt Volcano (Roman and Cashman, 2018). Our study highlights that melt embayment geospeedometry, while largely a retrospective approach to understanding magma ascent rates, can potentially identify systems that experience slow magmatic ascent leading to staging in the crust which may not be detectable in all cases via seismic monitoring. Where in some systems this will allow for the merging of monitoring and petrologic approaches for refining models of magma ascent, in systems that lack monitoring datasets (i.e., pre-historic eruptions), the embayment could provide important insights into the behavior of magma ascent to inform on future monitoring efforts.

Lastly, we highlight some outstanding challenges for the embayment modeling community. Most notably, the non-uniqueness of best-fit solutions in H_2O -saturated systems, especially for approximating the initial decompression rate, begs further investigation into whether modeling a single diffusive species is a reliable approach to recovering magma decompression rates, especially in the absence of any independent decompression rate estimates. Secondly, the ability of EDiTS to successfully model both synthetic and experimental embayment volatile profiles produced by constant-rate decompression (i.e., a false positive result) further highlights the challenges of embayment modeling and interpretation. Again, however, we argue that because magma ascent is dynamically a nonlinear process, this result should not impact the application of EDiTS to natural systems. Finally, embayment modeling assumptions (e.g., degassing mechanism; deGraffenried and Shea, 2021) shown to have significant influence on calculated decompression rates require further investigation and incorporation into future iterations of embayment diffusion models. Numerical conduit models that consider the influence of disequilibrium degassing of H_2O and CO_2 on predicted decompression rates have been recently developed for basaltic magmas (e.g., La Spina et al., 2016, 2021, 2022; Bamber et al., 2022, 2024). The embayment modeling community would similarly benefit from the incorporation of these complexities in future iterations of embayment models for all melt compositions.

5. Conclusions

In this study, we have developed, validated, and applied a new two-stage decompression-diffusion model for melt embayments: Embayment Decompression in Two Stages (EDiTS). After successfully numerically benchmarking EDiTS, we used high pressure-temperature decompression experiments on natural embayments to determine how faithfully they record, and how reliably EDiTS recovers, the imposed decompression paths. While EDiTS performs well in mixed-volatile ($H_2O + CO_2$) systems, we note challenges in applying EDiTS to (1) H_2O -saturated systems and (2) embayment volatile profiles generated both synthetically and experimentally by a constant-rate decompression (i.e., false positive results). To address (1), we suggest using the interior embayment saturation pressures to constrain the range of model parameters cycled through. For (2), we argue that, because magma dynamically does not experience constant, linear decompression, these false positive results do not necessarily have any bearing on the application of EDiTS to natural systems.

Through application of EDiTS to existing embayment datasets, we find that initial decompression in the deep conduit can occur over hours, while the shallow conduit is characterized by much faster decompression on the order of minutes. For the May 18th, 1980 Plinian eruption of Mount St. Helens in particular, EDiTS is able to reconcile embayment-based estimates of magma decompression with both real-time observations and independent petrologic recorders. Altogether, our work emphasizes that embayments can preserve nuanced records of magma ascent and should be leveraged in actively monitored settings for an integrated understanding of magma movement from the deep conduit to the surface. This is especially true for systems containing multiple diffusing species (e.g., H_2O , CO_2 , S). We thus recommend the development of similar multi-stage decompression models applicable to and parameterized for more intermediate to basaltic melt compositions. As these are also more frequently active systems, the volcano community would be positioned to pair embayment decompression rates with robust, independent observations of magma ascent and eruption.

CRedit authorship contribution statement

Behnaz Hosseini: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Madison Myers:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have included GitHub and Zenodo links for the EDiTS model presented in the paper: <https://zenodo.org/record/10042159>. We also have included experimental and analytical data in the supplement.

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Appendix A. Supplementary data

All data associated with this study are presented in this paper or otherwise available in the supplemental document. Appendix A. Supplementary Material contains detailed experimental and analytical procedures and results, as well as schematics of the EDiTS model architecture, numerical benchmarking results, and the experimental capsule set-up. Supplementary data to this article can be found online at [<https://doi.org/10.1016/j.jvolgeores.2024.108211>].

References

- Andrews, B.J., Befus, K.S., 2020. Supersaturation Nucleation and Growth of Plagioclase: A numerical model of decompression-induced crystallization. *Contrib. Mineral. Petrol.* 175 (23), 1–20. <https://doi.org/10.1007/s00410-020-1660-9>.
- Bamber, E.C., La Spina, G., Arzilli, F., de 'Michieli Vitturi, M., Polacci, M., Hartley, M.E., Petrelli, M., Fellowes, J., Burton, M., 2022. Basaltic Plinian eruptions at Las Sierritas-Masaya volcano driven by cool storage of crystal-rich magmas. *Commun. Earth Environ.* 3 (1), 1–17. <https://doi.org/10.1038/s43247-022-00585-5>.
- Bamber, E.C., La Spina, G., Arzilli, F., Polacci, M., Mancini, L., de 'Michieli Vitturi, M., Andronico, D., Corsaro, R.A., Burton, M.R., 2024. Outgassing behaviour during highly explosive basaltic eruptions. *Commun. Earth Environ.* 5 (1), 1–16. <https://doi.org/10.1038/s43247-023-01182-w>.
- Befus, K.S., Ruefer, A.C., Allison, C.M., Thompson, J.O., 2022. Quartz-hosted inclusions and embayments reveal storage, fluxing, and ascent of the Mesa Falls Tuff, Yellowstone. *Earth Planet. Sci. Lett.* 601, 1–13. <https://doi.org/10.1016/j.epsl.2022.117909>.
- Blundy, J., Cashman, K., 2005. Rapid decompression-driven crystallization recorded by melt inclusions from Mount St. Helens volcano. *Geology* 33 (10), 793–796. <https://doi.org/10.1130/G21668.1>.
- Blundy, J., Cashman, K., Humphreys, M., 2006. Magma heating by decompression-driven crystallization beneath andesite volcanoes. *Nature* 443 (7107), 76–80. <https://doi.org/10.1038/nature05100>.
- Carey, S., Sigurdsson, H., 1985. The May 18, 1980 eruption of Mount St. Helens: 2. Modeling of dynamics of the Plinian phase. *J. Geophys. Res.: Solid Earth* 90 (B4), 2948–2958. <https://doi.org/10.1029/JB090iB04p02948>.
- Carey, S., Sigurdsson, H., Gardner, J.E., Criswell, W., 1990. Variations in column height and magma discharge during the May 18, 1980 eruption of Mount St. Helens. *J. Volcanol. Geotherm. Res.* 43 (1–4), 99–112. [https://doi.org/10.1016/0377-0273\(90\)90047-J](https://doi.org/10.1016/0377-0273(90)90047-J).
- Caricchi, L., Townsend, M., Rivalta, E., Namiki, A., 2021. The build-up and triggers of volcanic eruptions. *Nat. Rev. Earth Environ.* 2 (7), 458–476. <https://doi.org/10.1038/s43017-021-00174-8>.
- Cichy, S.B., Botcharnikov, R.E., Holtz, F., Behrens, H., 2011. Vesiculation and microlite crystallization induced by decompression: A case study of the 1991–1995 Mt Unzen eruption (Japan). *J. Petrol.* 52 (7–8), 1469–1492. <https://doi.org/10.1093/ptrology/egq072>.
- deGraffenried, R., Shea, T., 2021. Using volatile element concentration profiles in crystal-hosted melt embayments to estimate magma decompression rate: Assumptions and inherited errors. *Geochem. Geophys. Geosyst.* 22, 1–18. <https://doi.org/10.1029/2021GC009672>.
- Eichelberger, J.C., 1995. Silicic volcanism: Ascent of viscous magmas from crustal reservoirs. *Ann. Rev. Earth Planet. Sci.* 23, 41–63. <https://doi.org/10.1146/annurev.ea.23.050195.000353>.
- Eichelberger, J.C., Hayes, D.B., 1982. Magmatic model for the Mount St. Helens blast of May 18, 1980. *J. Geophys. Res. Solid Earth* 87 (B9), 7727–7738. <https://doi.org/10.1029/JB087iB09p07727>.
- Elms, H.C., Myers, M.L., Nichols, A.R.L., Wallace, P.J., Wilson, C.J.N., Barker, S.J., Charlier, B.L.A., 2023. Pre-eruptive rhyolite magma ascent rate is rapid and independent of eruption size: A case study from Ōkataina Volcanic Centre, Aotearoa New Zealand. *Bullet. Volcanol.* 85 (4), 1–20. <https://doi.org/10.1007/s00445-023-01630-7>.
- Endo, E.T., Malone, S.D., Nason, L.L., 1981. The 1980 eruptions of Mount St. Helens, Washington. *US Geological Survey Professional Paper* 1250, 93–107.
- Ferguson, D.J., Gonnermann, H.M., Ruprecht, P., Plank, T., Hauri, E.H., Houghton, B.F., Swanson, D.A., 2016. Magma decompression rates during explosive eruptions of Kilauea volcano, Hawaii, recorded by melt embayments. *Bull. Volcanol.* 78 (10), 1–12. <https://doi.org/10.1007/s00445-016-1064-x>.
- Freda, C., Baker, D.R., Romano, C., Scarlato, P., 2003. Water diffusion in natural potassic melts. *Geol. Soc. Lond. Spec. Publ.* 213 (1), 53–62. <https://doi.org/10.1144/GSL.SP.2003.213.01.04>.
- Freda, C., Baker, D.R., Scarlato, P., 2005. Sulfur diffusion in basaltic melts. *Geochim. Cosmochim. Acta* 69 (21), 5061–5069. <https://doi.org/10.1016/j.gca.2005.02.002>.
- Georgeais, G., Koga, K.T., Moussallam, Y., Rose-Koga, E.F., 2021. Magma decompression rate calculations with EMBER: A user-friendly software to model diffusion of H_2O , CO_2 , and S in melt embayments. *Geochem. Geophys. Geosyst.* 22 (7), 1–20. <https://doi.org/10.1029/2020GC009542>.
- Geshi, N., Yamasaki, T., Miyagi, I., Conway, C.E., 2021. Magma chamber decompression during explosive caldera-forming eruption of Aira caldera. *Commun. Earth Environ.* 2 (1), 1–10. <https://doi.org/10.1038/s43247-021-00272-x>.
- Ghiorso, M.S., Gualda, G.A., 2015. An H_2O – CO_2 mixed fluid saturation model compatible with rhyolite-MELTS. *Contrib. Mineral. Petrol.* 169, 1–30. <https://doi.org/10.1007/s00410-015-1141-8>.
- Gonnermann, H.M., Manga, M., 2013. Dynamics of Magma Ascent in the Volcanic Conduit. *Modeling volcanic processes: The Physics and Mathematics of Volcanism*, p. 55.
- Hajimirza, S., Gonnermann, H.M., Gardner, J.E., 2021. Reconciling bubble nucleation in explosive eruptions with geospeedometers. *Nat. Commun.* 12 (1), 1–8. <https://doi.org/10.1038/s41467-020-20541-1>.
- Hammer, J.E., Rutherford, M.J., 2002. An experimental study of the kinetics of decompression-induced crystallization in silicic melt. *J. Geophys. Res. Solid Earth* 107 (B1), ECV–8. <https://doi.org/10.1029/2001JB000281>.
- Harris, M., Hosseini, B., Myers, M., Bouley, L., 2024. Reconciling petrologic magma ascent speedometers for the June 12th, 1991 eruption of Mount Pinatubo. *Volcanica. Philippines* 7 (1), 117–133. <https://doi.org/10.30909/vol.07.01.117133>.

- Hosseini, B., Myers, M.L., Watkins, J.M., Harris, M.A., 2023. Are we recording? Putting embayment speedometry to the test using high pressure-temperature decompression experiments. *Geochem. Geophys. Geosyst.* 24 (6), 1–18. <https://doi.org/10.1029/2022GC010770>.
- Humphreys, M.C., Menand, T., Blundy, J.D., Klimm, K., 2008. Magma ascent rates in explosive eruptions: Constraints from H₂O diffusion in melt inclusions. *Earth Planet. Sci. Lett.* 270 (1–2), 25–40. <https://doi.org/10.1016/j.epsl.2008.02.041>.
- Iacovino, K., Matthews, S., Wieser, P.E., Moore, G.M., Bégué, F., 2021. VESCAL Part I: An open-source thermodynamic model engine for mixed volatile (H₂O–CO₂) solubility in silicate melts. *Earth Space Sci.* 8 (11), 1–55. <https://doi.org/10.1029/2020EA001584>.
- Kieffer, S.W., 1981. Blast dynamics at Mount St Helens on 18 May 1980. *Nature* 291 (5816), 568–570. <https://doi.org/10.1038/291568a0>.
- La Spina, G., Burton, M., de Micheli Vitturi, M., Arzilli, F., 2016. Role of syneruptive plagioclase disequilibrium crystallization in basaltic magma ascent dynamics. *Nat. Commun.* 7 (1), 1–10. <https://doi.org/10.1038/ncomms13402>.
- La Spina, G., Arzilli, F., Llewellyn, E.W., Burton, M.R., Clarke, A.B., Vitturi, M.D.M., Polacci, M., Hartley, M.E., Di Genova, D., Mader, H.M., 2021. Explosivity of basaltic lava fountains is controlled by magma rheology, ascent rate and outgassing. *Earth Planet. Sci. Lett.* 553 (1), 1–11. <https://doi.org/10.1016/j.epsl.2020.116658>.
- La Spina, G., Arzilli, F., Burton, M.R., Polacci, M., Clarke, A.B., 2022. Role of volatiles in highly explosive basaltic eruptions. *Commun. Earth Environ.* 3 (1), 1–13. <https://doi.org/10.1038/s43247-022-00479-6>.
- Liu, Y., Zhang, Y., Behrens, H., 2005. Solubility of H₂O in rhyolitic melts at low pressures and a new empirical model for mixed H₂O–CO₂ solubility in rhyolitic melts. *J. Volcanol. Geotherm. Res.* 143 (1–3), 219–235. <https://doi.org/10.1016/j.jvolgeores.2004.09.019>.
- Liu, Y., Anderson, A.T., Wilson, C.J., 2007. Melt pockets in phenocrysts and decompression rates of silicic magmas before fragmentation. *J. Geophys. Res.: Solid Earth* 112, 1–12. doi:10.1029/2006JB004500.
- Lloyd, A.S., Ruprecht, P., Hauri, E.H., Rose, W., Gonnermann, H.M., Plank, T., 2014. NanoSIMS results from olivine-hosted melt embayments: Magma ascent rate during explosive basaltic eruptions. *J. Volcanol. Geotherm. Res.* 283, 1–18. <https://doi.org/10.1016/j.jvolgeores.2014.06.002>.
- Mangan, M., Sisson, T., 2000. Delayed, disequilibrium degassing in rhyolite magma: Decompression experiments and implications for explosive volcanism. *Earth Planet. Sci. Lett.* 183 (3–4), 441–455. [https://doi.org/10.1016/S0012-821X\(00\)00299-5](https://doi.org/10.1016/S0012-821X(00)00299-5).
- Martin, L.G., 2005. The controlling effect of viscous dissipation on magma flow in silicic conduits. *J. Volcanol. Geotherm. Res.* 143, 17–28. <https://doi.org/10.1016/j.jvolgeores.2004.09.008>.
- Martin, L.G., Ghiorso, M.S., 2001. Adiabatic temperature changes of magma–gas mixtures during ascent and eruption. *Contrib. Mineral. Petrol.* 141, 307–321. <https://doi.org/10.1007/s004100000210>.
- Melnik, O., Sparks, S., 2006. Transient Models of Conduit Flows During Volcanic Eruptions. Geological Society of London. <https://doi.org/10.1144/IAVCEI001.16>.
- Moussallam, Y., Rose-Koga, E.F., Koga, K.T., Médard, E., Bani, P., Devidal, J.-L., Tari, D., 2019. Fast ascent rate during the 2017–2018 Plinian eruption of Ambae (Aoba) volcano: A petrological investigation. *Contrib. Mineral. Petrol.* 174 (11), 1–24. <https://doi.org/10.1007/s00410-019-1625-z>.
- Myers, M.L., Wallace, P.J., Wilson, C.J., Watkins, J.M., Liu, Y., 2018. Ascent rates of rhyolitic magma at the onset of three caldera-forming eruptions. *Am. Mineral.* 103 (6), 952–965. <https://doi.org/10.2138/am-2018-6225>.
- Myers, M.L., Druitt, T.H., Schiavi, F., Gurioli, L., Flaherty, T., 2021. Evolution of magma decompression and discharge during a Plinian event (late Bronze-Age eruption, Santorini) from multiple eruption-intensity proxies. *Bull. Volcanol.* 83 (3), 1–17. <https://doi.org/10.1007/s00445-021-01438-3>.
- Newcombe, M.E., Plank, T., Barth, A., Asimow, P.D., Hauri, E., 2020. Water-in-olivine magma ascent chronometry: Every crystal is a clock. *J. Volcanol. Geotherm. Res.* 398, 1–17. <https://doi.org/10.1016/j.jvolgeores.2020.106872>.
- Newman, S., Lowenstern, J.B., 2002. VolatileCalc: A silicate melt–H₂O–CO₂ solution model written in Visual basic for excel. *Comput. Geosci.* 28 (5), 597–604. [https://doi.org/10.1016/S0098-3004\(01\)00081-4](https://doi.org/10.1016/S0098-3004(01)00081-4).
- Ni, H., Zhang, Y., 2008. H₂O diffusion models in rhyolitic melt with new high pressure data. *Chem. Geol.* 250 (1–4), 68–78. <https://doi.org/10.1016/j.chemgeo.2008.02.011>.
- Nowak, M., Behrens, H., 1997. An experimental investigation on diffusion of water in haplogranitic melts. *Contrib. Mineral. Petrol.* 126 (4), 365–376. <https://doi.org/10.1007/s004100050256>.
- Nowak, M., Schreen, D., Spickenbom, K., 2004. Argon and CO₂ on the race track in silicate melts: A tool for the development of a CO₂ speciation and diffusion model. *Geochim. Cosmochim. Acta* 68 (24), 5127–5138. <https://doi.org/10.1016/j.gca.2004.06.002>.
- Rasmussen, D.J., Plank, T.A., Roman, D.C., Power, J.A., Bodnar, R.J., Hauri, E.H., 2018. When does eruption run-up begin? Multidisciplinary insight from the 1999 eruption of Shishaldin volcano. *Earth Planet. Sci. Lett.* 486, 1–14. <https://doi.org/10.1016/j.epsl.2018.01.001>.
- Roman, D.C., Cashman, K.V., 2018. Top-down precursory volcanic seismicity: Implications for ‘stealth’ magma ascent and long-term eruption forecasting. *Front. Earth Sci.* 6, 124. <https://doi.org/10.3389/feart.2018.00124>.
- Ruth, D.C., Costa, F., Bouvet de Maisonneuve, C., Franco, L., Cortés, J.A., Calder, E.S., 2018. Crystal and melt inclusion timescales reveal the evolution of magma migration before eruption. *Nat. Commun.* 9 (1), 1–9. <https://doi.org/10.1038/s41467-018-05086-8>.
- Rutherford, M.J., Hill, P.M., 1993. Magma ascent rates from amphibole breakdown: An experimental study applied to the 1980–1986 Mount St. Helens eruptions. *J. Geophys. Res. Solid Earth* 98 (B11), 19667–19685. <https://doi.org/10.1029/93JB01613>.
- Saalfeld, M.A., Myers, M., deGraffenried, R., Shea, T., Waelkens, C., 2022. On the rise: Using reentrants to extract magma ascent rates in the Bandelier Tuff caldera complex, New Mexico, USA. *Bull. Volcanol.* 84, 1–21. <https://doi.org/10.1007/s00445-021-01518-4>.
- Scandone, R., Malone, S.D., 1985. Magma supply, magma discharge and readjustment of the feeding system of Mount St. Helens during 1980. *J. Volcanol. Geotherm. Res.* 23 (3–4), 239–262. [https://doi.org/10.1016/0377-0273\(85\)90036-8](https://doi.org/10.1016/0377-0273(85)90036-8).
- Sparks, R.S.J., 2003. Dynamics of Magma Degassing doi.org/10.1144/GSL.SP.2003.213.01.02.
- Toramaru, A., 2006. BND (bubble number density) decompression rate meter for explosive volcanic eruptions. *J. Volcanol. Geotherm. Res.* 154 (3–4), 303–316. <https://doi.org/10.1016/j.jvolgeores.2006.03.027>.
- Voight, T., Blacken, H., Jana, R.J., Douglass, P.M., 1981. The 1980 eruptions of Mount St. Helens, Washington. US Geological Survey Professional Paper 1250, 347–377.
- Wei, Z., Ruefer, A.C., Pamukcu, A.S., Suckale, J., 2024. Deciphering clues regarding magma composition encoded in quartz-hosted embayments and melt inclusions through direct numerical simulations. *J. Geophys. Res. Solid Earth* 129 (4), 1–25. <https://doi.org/10.1029/2023JB028080>.
- Witham, F., Blundy, J., Kohn, S.C., Lesne, P., Dixon, J., Churakov, S.V., Botcharnikov, R., 2012. SolEx: A model for mixed COHSL-volatile solubilities and exsolved gas compositions in basalt. *Comput. Geosci.* 45, 87–97. <https://doi.org/10.1016/j.cageo.2011.09.021>.
- Wong, Y.Q., Segall, P., 2019. Numerical analysis of time-dependent conduit magma flow in dome-forming eruptions with application to Mount St. Helens 2004–2008. *J. Geophys. Res. Solid Earth* 124 (11), 11251–11273. <https://doi.org/10.1029/2019JB017585>.
- Zhang, Y., Behrens, H., 2000. H₂O diffusion in rhyolitic melts and glasses. *Chem. Geol.* 169 (1–2), 243–262. [https://doi.org/10.1016/S0009-2541\(99\)00231-4](https://doi.org/10.1016/S0009-2541(99)00231-4).
- Zhang, Y., Ni, H., 2010. Diffusion of H, C, and O components in silicate melts. *Rev. Mineral. Geochem.* 72 (1), 171–225. <https://doi.org/10.2138/rmg.2010.72.5>.
- Zhang, Y., Xu, Z., Zhu, M., Wang, H., 2007. Silicate melt properties and volcanic eruptions. *Rev. Geophys.* 45 (4), 1–27. <https://doi.org/10.1029/2006RG000216>.
- Zhang, Y., Ni, H., Chen, Y., 2010. Diffusion data in silicate melts. *Rev. Mineral. Geochem.* 72 (1), 311–408. <https://doi.org/10.2138/rmg.2010.72.8>.
- Zuccarello, F., Schiavi, F., Viccaro, M., 2022. The eruption run-up at Mt. Etna volcano: Constraining magma decompression rates and their relationships with the final eruptive energy. *Earth Planet. Sci. Lett.* 597, 1–13. <https://doi.org/10.1016/j.epsl.2022.117821>.