Compartmentalization of Axial Seamount's magma reservoir inferred by analytical and numerical deformation modeling with realistic geometry

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Key Points:

- Uniform pressurization of Axial Seamount's seismically imaged magma reservoir does not adequately fit the observed geodetic data
- Our models estimate that Axial's magma reservoir inflated by 0.054-0.060 km^3 during the inter-eruptive recharge period between 2016-2020
- Axial's magma reservoir is likely compartmentalized, with magma accumulating in sills along the western-central edge of the magma reservoir

Abstract

Axial Seamount is a submarine volcano on the Juan de Fuca Ridge with enhanced magma supply from the Cobb hotspot. We compare several deformation model configurations to explore how the spatial component of Axial's deformation time series relates to magma reservoir geometry imaged by multi-channel seismic (MCS) surveys. To constrain the models, we use vertical displacements from seafloor pressure sensors and repeat autonomous underwater vehicle (AUV) bathymetric surveys between 2016-2020. We show that implementing the MCS-derived 3D main magma reservoir (MMR) geometry with uniform pressure in a finite element model with uniform elastic host rock properties poorly fits the geodetic data. To test the hypothesis that there is compartmentalization within the MMR that results in heterogeneous pressure distribution, we compare analytical models using various horizontal sill configurations constrained by the MMR geometry. Using distributed pressure sources significantly improves the Root Mean Square Error (RMSE) between the inflation data and the models by an order of magnitude. The RMSE between the AUV data and the models is not improved as much, likely due to larger uncertainty of the AUV data. The models estimate the volume change for the 2016-2020 inter-eruptive inflation period to be between 0.054-0.060 km^3 and suggest that the MMR is compartmentalized, with most magma accumulating in sill-like bodies embedded in crystal mush along the western-central edge of the MMR. The results reveal the complexity of Axial's plumbing system and demonstrate the utility of integrating geodetic data and seismic imagery to gain insights into magma storage at active volcanoes.

Plain Language Summary

Axial Seamount is a submarine volcano on the Juan de Fuca Ridge (NE Pacific Ocean) with enhanced magma supply from the Cobb hotspot. Its frequent activity and long-term deformation time series covering eruptions in 1998, 2011 and 2015 make it an ideal place to study volcanic processes. Improved magma reservoir modeling at Axial will aid in understanding how magma transport and storage are related to surface deformation, seismicity, and eruption timing. Here we compare several models of Axial's magma reservoir to explore how the spatial component of the observed deformation at Axial compares to seismically imaged magma reservoir geometry. To constrain the models, we use vertical displacements covering an inflation period between 2016-2020, derived from pressure measurements collected at seafloor benchmarks and repeated bathymetric surveys. The models estimate the volume change for the 2016-2020 inflation period to be between 0.054-0.060 km^3. Our results suggest that Axial's magma reservoir is compartmentalized, with most magma accumulating in sill-like bodies embedded in crystal mush. The results reveal the spatial complexity of Axial's plumbing system and demonstrate how deformation data and seismic imagery can be used together to gain deeper insights into magma storage at active volcanoes.

1. Introduction

Axial Seamount is an active submarine volcano located at the intersection of the Juan de Fuca Ridge and the Cobb hotspot about 500 km west of the Oregon coast in the NE Pacific (Figure 1). It has erupted at least 52 times over the last 800 years (Clague et al., 2013), most recently in 1998, 2011, and 2015. A nearly continuous deformation time series from 1998 through the present covering the past 3 eruptions has revealed that Axial exhibits a relatively repeatable inflation-deflation cycle, which has allowed for two successful eruption forecasts (Chadwick et al., 2012; Nooner & Chadwick, 2016). Even though Axial itself does not pose a direct threat to humans because of its remoteness, insight gleaned from observations made at Axial contribute to a growing body of knowledge about eruptive precursors that can be applied to more threatening locations (Acocella et al., 2024).

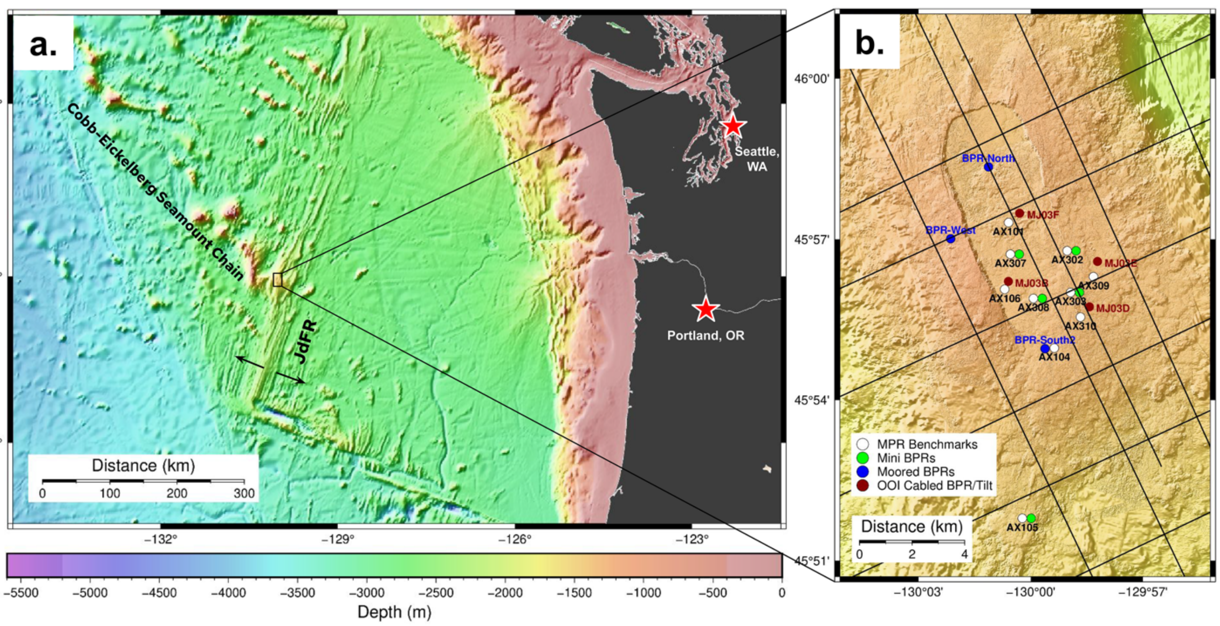

Figure 1. a) Axial Seamount's tectonic setting at the intersection of the Juan de Fuca Ridge (JdFR) and the Cobb hotspot. b) Zoom-in of Axial's summit caldera with geodetic instrumentation as of 2020 labeled. White dots are benchmarks where campaign-style mobile pressure recorder (MPR) measurements are made, green dots are mini bottom pressure recorders (BPRs), blue dots are moored BPRs, and red dots are BPRs and tiltmeters connected to the Ocean Observatories Initiative (OOI) cabled observatory. Black lines are seismic lines (Carbotte et al., 2008) downward extrapolated by Arnulf et al., 2018 to image the main magma reservoir (MMR) geometry as used in this study (see Arnulf et al., 2018 for full extent of lines used).

Deformation models of Axial have evolved from simple to more complex over the years as more geodetic data have become available. A point source (Mogi, 1958) was initially used as the pressure source when few observations were available to constrain models and little was known about the actual geometry of Axial's magma storage system (Chadwick et al., 2006; Nooner & Chadwick, 2009). Once more benchmarks for pressure measurements were added and more analytical model geometries were considered, a steeply dipping prolate spheroid geometry became the best-fit model (Hefner et al., 2020; Nooner & Chadwick, 2016). The prolate spheroid model depth, location, and geometry were somewhat consistent with a set of vertically stacked deep sills later imaged by multi-channel seismic (MCS) data and interpreted by Carbotte et al., (2020). However, as autonomous underwater vehicle (AUV) repeat bathymetry data (Caress et al., 2020) has begun to provide more spatial coverage and therefore additional constraints for deformation modeling than the limited number of point-pressure observations alone, a rectangular horizontal sill deformation model with about the same outline as the summit caldera has been found to fit both the AUV and pressure data better than a prolate spheroid (Hefner et al., 2021).

The acquisition of multi-channel seismic (MCS) data at Axial in 2002 (Arnulf et al., 2014, 2018; Carbotte et al., 2020) provided a high-resolution view of the magma reservoir geometry beneath the summit of Axial for the first time. Given the simplicity of the previous analytical deformation models, a logical next step was to investigate how a more realistic geometry of the magmatic system relates to deformation observed at the surface, in order to add more physical meaning to the modeling results. Arnulf et al., (2018) used MCS data to define the 3-D geometry and location of the main magma reservoir (MMR) beneath the summit caldera at Axial, as well as a secondary magma reservoir (SMR) located ~ 10 km to the east-southeast. The MMR vertically extends from 1.1-2.8 km depth below seafloor, is slightly offset from Axial's caldera to the east, and extends beyond the caldera to the north and south (Figure 2). The deep stacked sills imaged by Carbotte et al., (2020) are located below the southern half of the MMR between 3-5 km below the seafloor.

We constructed deformation models constrained by the MMR geometry in several ways. First, we directly used the 3D MMR geometry with uniform internal pressure in a finite element model (FEM), but we found that doing so provides very poor fit to the geodetic data. We then constructed and considered several analytical deformation models as alternatives, including: 1) approximating the MMR shape using one rectangular horizontal sill, 2) approximating the MMR shape using 3 rectangular non-horizontal sills, 3) allowing for non-uniform pressure distribution in a 2D horizontal sill at the average depth of the MMR roof, and 4) allowing for non-uniform pressure distributed over the 3D MMR roof. The models are constrained by the observations of vertical deformation from seafloor pressure data and repeated AUV bathymetric surveys during Axial's current inter-eruption phase between 2016-2020. Our inversion results suggest that the MMR is likely compartmentalized, which is consistent with current thinking on magma reservoir structure.

2. Deformation data

Bottom pressure recorders (BPRs) measure pressure at the seafloor; if the seafloor is uplifted, there is less water column above it and therefore lower pressure. Similarly, if the seafloor subsides, the BPR measures higher pressure. The pressure data are converted to depth after removing tidal signals (Eble et al., 1989). BPRs were deployed at Axial's summit caldera in 1998 when Axial's first observed eruption occurred (Chadwick et al., 2013; Dziak & Fox, 1999; Embley et al., 1999; Fox, 1999; Fox et al., 2001). After a two-year gap in coverage, the deformation time series resumed in 2000 with an array of seafloor benchmarks and the time series has been continuous through the present (Figure 1; Chadwick et al., 2006, 2012, 2022; Nooner & Chadwick, 2009, 2016). Since 2000, BPR measurements have been supplemented by measurements from mobile pressure recorders (MPRs), which are used in campaign-style surveys at seafloor benchmarks with a remotely operated vehicle (ROV) every 1-2 years to correct for the BPRs' long-term drift where the two are co-located (Chadwick et al., 2006). We used the MPR data for our study instead of BPR data because there were more MPR measurement locations in 2016-2020 and we are more interested in the spatial component of deformation than the temporal component.

Bathymetric surveys at 1-m scale have been conducted at Axial since 2006 using multibeam sonar equipped AUVs, first to obtain comprehensive coverage of the volcanic terrain, and then to measure the extent and thickness of lava flows from the 2011 and 2015 eruptions through differencing of repeated surveys (Caress et al., 2012; Chadwick et al., 2016). Beginning after the most recent eruption in 2015, a new sparse pattern of AUV survey lines extending well outside the caldera (Figure 2) was established to measure vertical surface deformation by differencing (Caress et al., 2020); this pattern has been repeated each summer since except 2021. Differencing the repeated components of the surveys reveals vertical surface deformation over a broader area than from the pressure sensors alone. However, compared to the MPR data which has an accuracy of ±1 cm, the AUV repeat bathymetry data have a lower vertical displacement accuracy of ± 20 cm. We used AUV vertical displacement data between two surveys in 2016 and 2020 (Figure 2). An AUV bathymetric survey was also conducted in 2015, but this survey apparently had higher errors than subsequent surveys, because the AUV depth changes between 2015-2020 poorly match the MPR depth changes from the same time period. Since MPR measurements were made in 2015 and 2017 (but not in 2016), we estimated the uplift values in 2016 at the MPR benchmarks by interpolating between the 2015 and 2017 MPR measurements assuming a linear deformation rate. The BPR record shows that deformation at the center of the caldera during this time period was not entirely linear (Chadwick et al., 2022). The benchmark at the center of the caldera had uplifted by 55 cm from mid-2015 to mid-2016, about 10 cm shallower in summer of 2016 than a linear interpolation would predict (Figure S1 in Supplementary Material). The deformation rate is highest at this benchmark compared to the other benchmarks, so our linear interpolation introduces an additional uncertainty of ≤10 cm in the estimated 2016 benchmark depths. Nevertheless, the estimated 2016-2020 depth changes at the benchmarks agree relatively well with the 2016-2020 AUV data (Figure S2 in Supplementary Material).

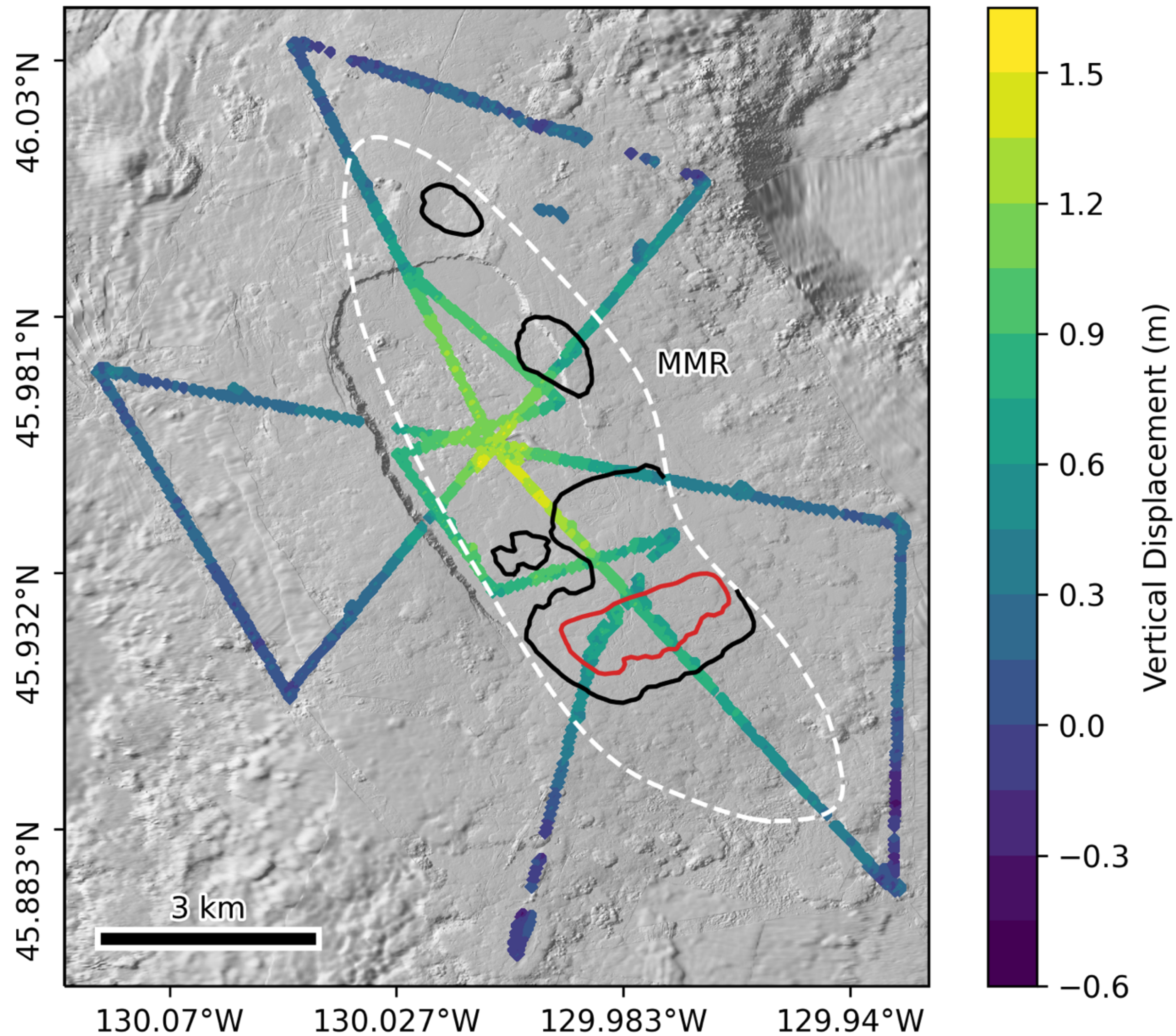

Figure 2. AUV repeat bathymetry data covering 2016-2020. Colors represent depth changes between AUV surveys. The MMR is outlined with a white dashed line. The shallowest parts of the MMR roof are shown with depth contours at -1250m and -1500m (below seafloor) in red and black, respectively. Bathymetry is shown with shaded relief in the background.

We only used deformation data covering the inflation period from 2016 to 2020 to constrain our models because the main objective of our study is to investigate the spatial component of the deformation signal and its implications for the underlying magma storage system. Previous studies have shown that the spatial pattern of inflation does not vary significantly between different time periods (Nooner & Chadwick, 2016), except for major episodes of deflation during eruptions when slip on the caldera ring faults may contribute to the deformation field (Hefner et al., 2020).

3. Deformation modeling

Our objective was to improve upon previous deformation models by reconciling the MMR geometry with the observed spatial deformation pattern. To do this, we constructed a series of models with increasing complexity, all constrained/bounded by the MMR. Each is discussed in detail below. Table 1 contains a summary of model configurations, inversion methods, and performance. See Figures 3 and 4 for a comparison of model geometries. For all models, typical mechanical properties were used (Poisson's ratio = 0.25, shear modulus = 30 GPa, Young's modulus = 70 GPa; Turcotte & Schubert, 2014). Although a systematic sensitivity test of each model to mechanical properties is outside the scope of this study, we found in testing a range of reasonable mechanical property values for basalt specifically (based on Turcotte & Schubert 2014) for Model 3b resulted in a volume change estimate range of 0.053629 – 0.053749 km^3 (0.22% change). We expect that this would affect the depth and volume change estimates similarly for those models that allow the source depth(s) to vary.

	Model configuration	**Inversion method**	**Volume change (km^3)**	**RMSE$_{mpr}$ (m)**	**RMSE$_{auv}$ (m)**
Null model	N/A	N/A	N/A	0.864	0.639
Model 1	FEM, MMR with uniform internal pressure	Parameter search	0.173	0.312	0.254
Model 2a	Analytical, 1 rectangular, horizontal sill	MCMC	0.056	0.059	0.122
Model 2b	Analytical, 3 rectangular, non-horizontal sills	MCMC	0.06	0.047	0.097
Model 3a	Analytical, 2D horizontal grid of Okada sill sources	Least squares regression	0.06	0.009	0.130
Model 3b	Analytical, 3D Okada sill sources draped over MMR roof	Least squares regression	0.054	0.002	0.139

Table 1. Summary of model configurations, inversion methods, modeled volume changes, and Root Mean Square Error (RMSE) values between each model and the MPR and AUV data. RMSE values for a null model with no deformation are shown for comparison.

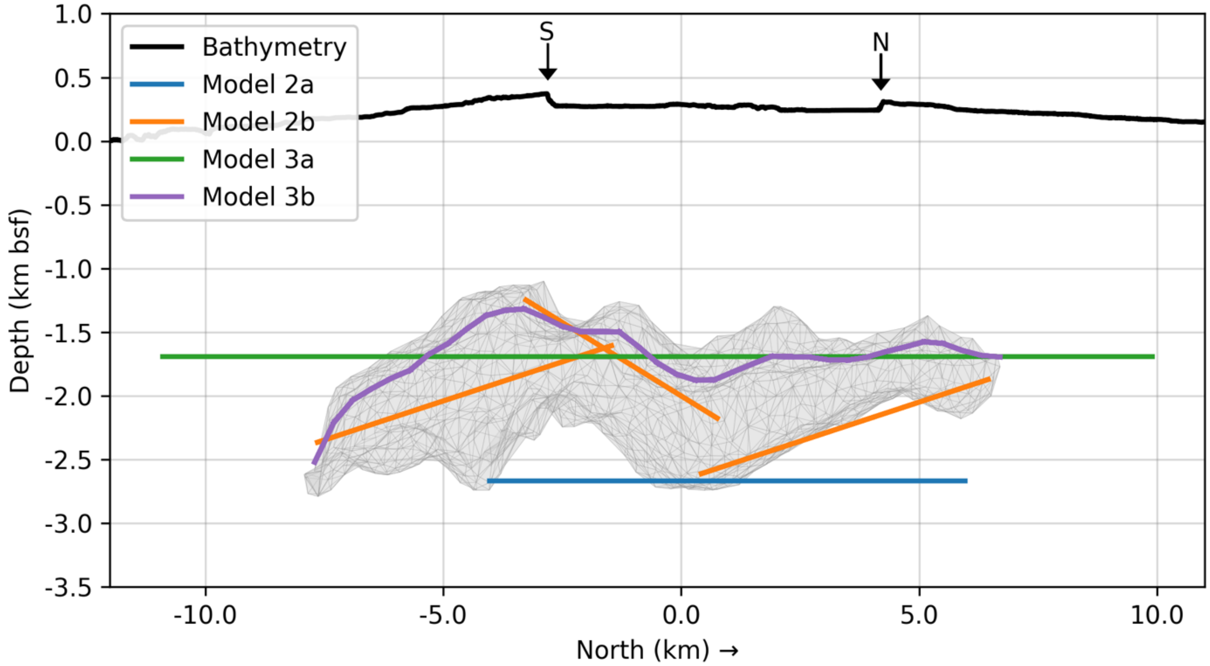

Figure 3. North/South cross section showing deformation model geometries investigated in this study. A bathymetric profile taken from North/South across the center of the caldera is also shown (black line); arrows point to the South and North caldera walls. The MMR geometry from Arnulf et al., (2018) is shown as a gray mesh and represents the Model 1 FEM source geometry. The other models are single or multiple combinations of rectangular sills (Okada, 1985; colored lines) with either uniform or distributed (non-uniform) opening. See text for details.

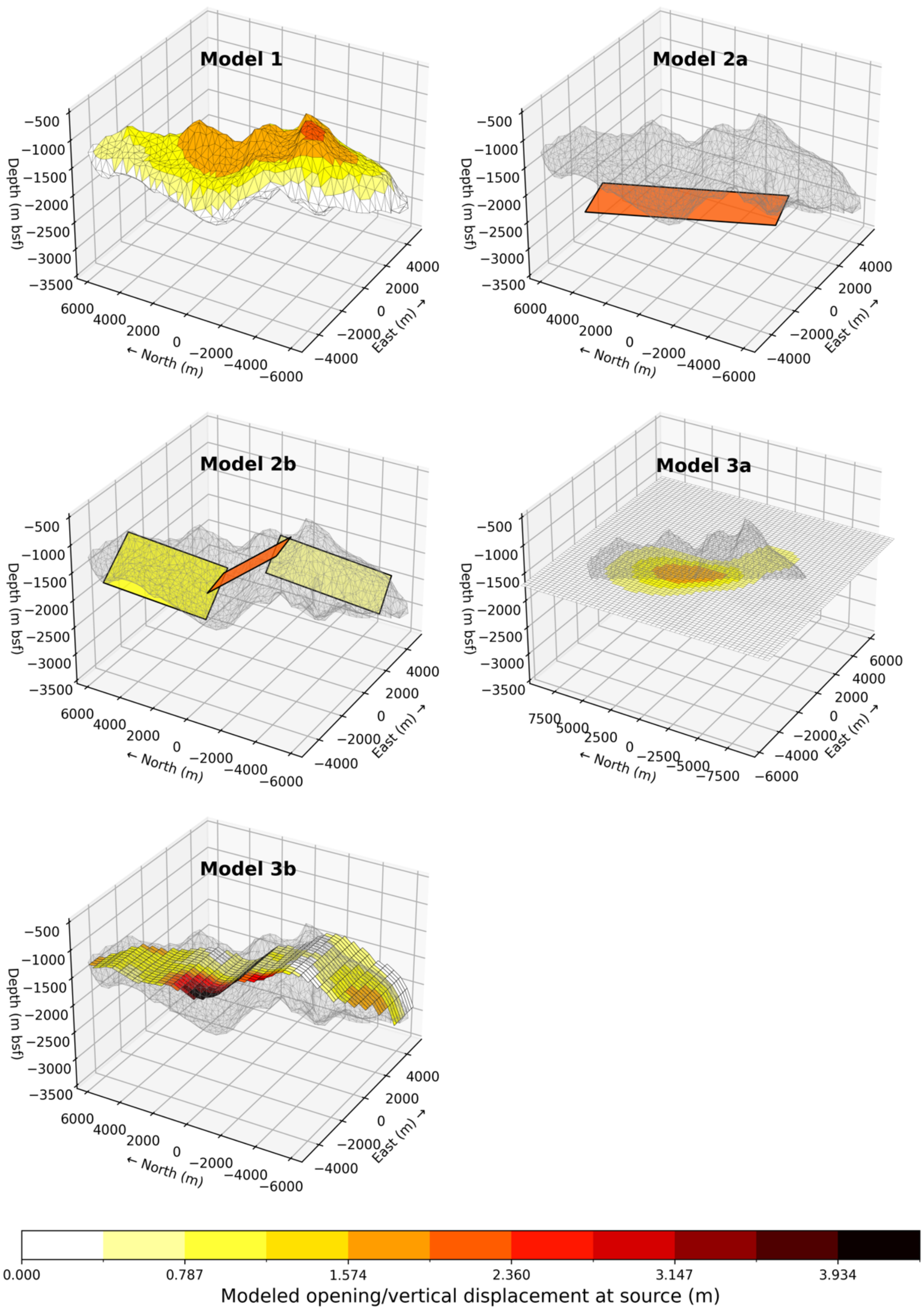

Figure 4. Oblique view of model configurations and modeled openings of each pressure source. For Model 1, the color scale represents vertical displacement at the source. For Models 2a-3b, the MMR is shown as a transparent gray mesh to provide context for the model geometries.

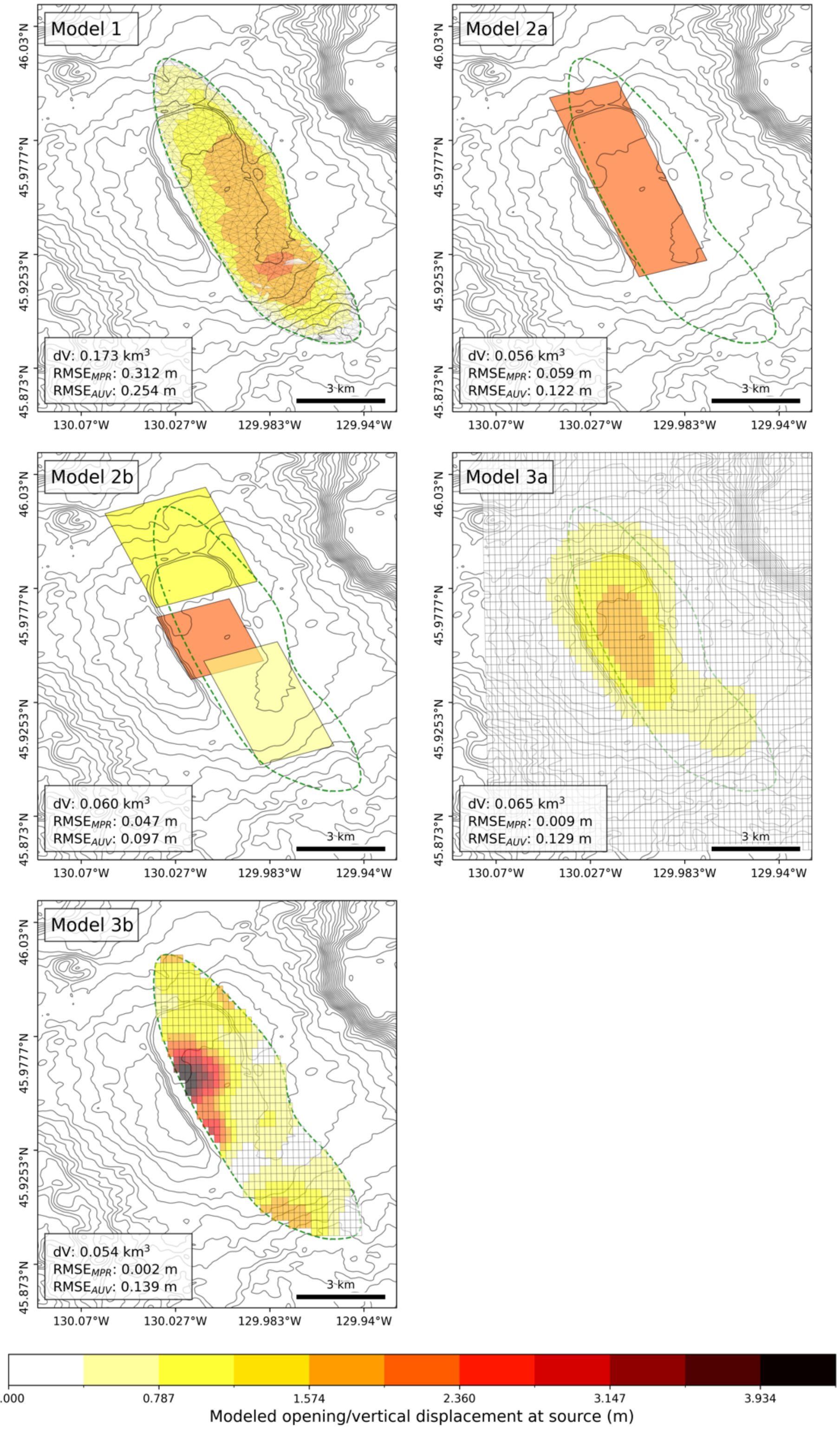

Figure 5. Map-view of model configurations and modeled openings of each pressure source overlain on bathymetric contours (contour interval is 35 m). For Model 1, the color scale represents vertical displacement at the source. The MMR is outlined in each plot with a dotted

green line. Each model's volume change (dV) and RMSE values between the model and the MPR and AUV data are shown in the lower left corner of each panel.

3.1. Model 1a: Finite element model with MMR geometry and uniform pressure

As a first step, we constructed an FEM using the MMR geometry from Arnulf et al., 2018 with a uniform pressure source. We started with a 3D point cloud defining the combined MMR roof and floor (see Arnulf et al., 2018 for more detail on how the roof and floor boundaries were defined). A 3D surface was constructed from the point cloud using a ball-pivoting algorithm, which starts with a seed triangle and creates new triangles by pivoting a ball with user-defined radius around the edges until it meets new points (Bernardini et al., 1999). This 3D surface was then loaded into Abaqus/CAE 2020, which we used to carry out the FEM simulations. To validate the FEM methodology, we compared an analytical prolate spheroid model (Yang et al., 1988) to an FEM with a pressurized cavity of the same dimensions and verified that both models predict the same surface deformation (Figure S3 in Supplementary Material).

The FEM domain measures 50 km long x 50 km wide x 30 km deep and the boundary conditions were specified by a free top surface, a roller constraint on the side surfaces, and a fixed bottom surface. We added bathymetry to the model using GMRT bathymetry data (Ryan et al., 2009). The effect of gravity was accounted for by adding an additional analysis step (prior to pressurization of the source) in which gravitational equilibrium is established by adding a pre-stress defined by hydrostatic equilibrium. This is an 'initial guess' which is used as a starting point to solve for the gravitational force that balances out the pressure force to result in near-zero ground deformation according to a defined threshold. We tested the effect of ocean loading by adding a downward hydrostatic pressure applied to the seafloor and found it to be negligible.

The MMR was incorporated by subtracting its volume from the domain and applying a uniform internal pressure on the cavity walls. The pressure was varied over many simulations to minimize the combined root-mean-squared error (RMSE) between the modeled surface displacements and the AUV and MPR data.

3.2. Models 2a and 2b: Analytical sill models using Bayesian inference

Model 2a is a single rectangular horizontal sill (Okada, 1985) and Model 2b consists of 3 non-horizontal rectangular sills constrained by the MMR geometry. We used the Volcanic and Seismic Source Modeling (VSM) package (Trasatti, 2022) to conduct joint inversions using Markov Chain Monte Carlo (MCMC) simulations to estimate the source parameters that produce surface deformation that best fits the AUV and MPR data.

For Model 2a, all inversion parameters were allowed to vary except for the dip angle of the sill, which was fixed at zero (horizontal). The sill's depth was bounded by the minimum and maximum MMR depth. For Model 2b, the 3-sill geometry was constrained by the MMR geometry by fixing the strike and dip angles in the inversion to follow the general trend of 3 main MMR segments (Figures 4 and 5). The locations of the sills were allowed to vary within 3 defined segments of the MMR volume and the sill opening values were allowed to vary freely. See Table 2 for a summary of fixed and best-fit variable parameters for Models 2a and 2b.

		Centroid Longitude	Centroid Latitude	Centroid depth (m bsf)	Length (m)	Width (m)	Strike	Dip	Opening (m)
Model 2a		-130.0100 ± 258 m	45.9637 ± 110 m	2666 ± 306	2561 ± 1119	9680 ± 253	341° ± 2	0	2.256 ± 0.682
Model 2b	**Sill 1**	-130.0249 ± 79 m	45.9968 ± 77 m	2241 ± 74	3829 ± 170	5170 ± 115	340°	-7°	1.285 ± 0.041
Model 2b	**Sill 2**	-130.0110 ± 83 m	45.9543 ± 97 m	1712 ± 70	2769 ± 166	3475 ± 164	340°	13°	2.071 ± 0.152
Model 2b	**Sill 3**	-129.9850 ± 126 m	45.9265 ± 175 m	1985 ± 206	2800 ± 207	5707.36 ± 325	340°	-7°	0.893 ± 0.076

Table 2. Summary of fixed and best-fit inverted parameters with standard deviations for Models 2a and 2b. The strike angle is the orientation of the plane measured clockwise from North according to Okada (1985) (i.e., strike = 0 if the plane is oriented North-South and dips to the East, strike = 90 if the plane is oriented East-West and dips to the South). Fixed parameters have red shading, parameters allowed to vary within the confines of the MMR geometry have yellow shading, and parameters allowed to freely vary have green shading.

3.3. Models 3a and 3b: 2D and 3D distributed pressure inversions

Inverting geodetic data to determine variable slip or opening distribution is a standard method for inferring co-seismic slip on faults (e.g., Moreno et al., 2009) and has also been applied in volcanic settings (e.g., Grandin et al., 2009). We performed two joint inversions of the MPR and AUV data following this approach. For Model 3a, we created a 2D horizontal grid of rectangular sill-patches at the average depth of the MMR roof and extending beyond the MMR boundary horizontally by 3 km in both the x and y directions. For Model 3b, we gridded the MMR roof point cloud into rectangular patches where each patch is defined by its position, length, width, strike, and dip. The patches are allowed to dip in the North/South direction but not in the East/West direction to create a continuous 3D grid with no gaps; this is appropriate since there is much more dip variation along the North/South direction of the MMR than there is along the East/West direction. The depths of the patches were defined by the average MMR roof depth at that location (Figures 3 and 4).

For both Models 3a and 3b, we treated each patch as a rectangular dislocation (Okada, 1985) and inverted for the opening value of each patch. Posed as a forward problem, the relationship between surface displacements and patch openings can be expressed by the linear system:

$$d = Gm$$

where d is the observation vector composed of vertical surface displacements, G is the Green's function matrix, and m is the vector of model parameters (patch openings). G was constructed by computing the expected vertical displacement at every observation point for each patch caused by a unit opening on that patch. To solve for m, we used a regularized linear least squares method which minimizes the objective function, $\phi(m)$:

$$\phi(m) = \| W(G \cdot m - d) \|_2^2 + \lambda^2 \| L \cdot m \|_2^2$$

The first term $\| W(G \cdot m - d) \|_2^2$ represents weighted misfit, i.e., the squared Euclidean norm difference between the observed data and the data predicted by the model, where W is a diagonal weight matrix which normalizes the contribution of the MPR and AUV datasets based on the relative uncertainties and the number of relative data points. The second term $\lambda^2 \| L \cdot m \|_2^2$ is the regularization term, where λ is the regularization parameter that controls the smoothness of the model, and L is the regularization matrix. The optimal λ value was chosen using an L-curve, where the preferred smoothness is located at the corner of the curve created by plotting roughness vs. the L2 norm of misfit (Figure 6).

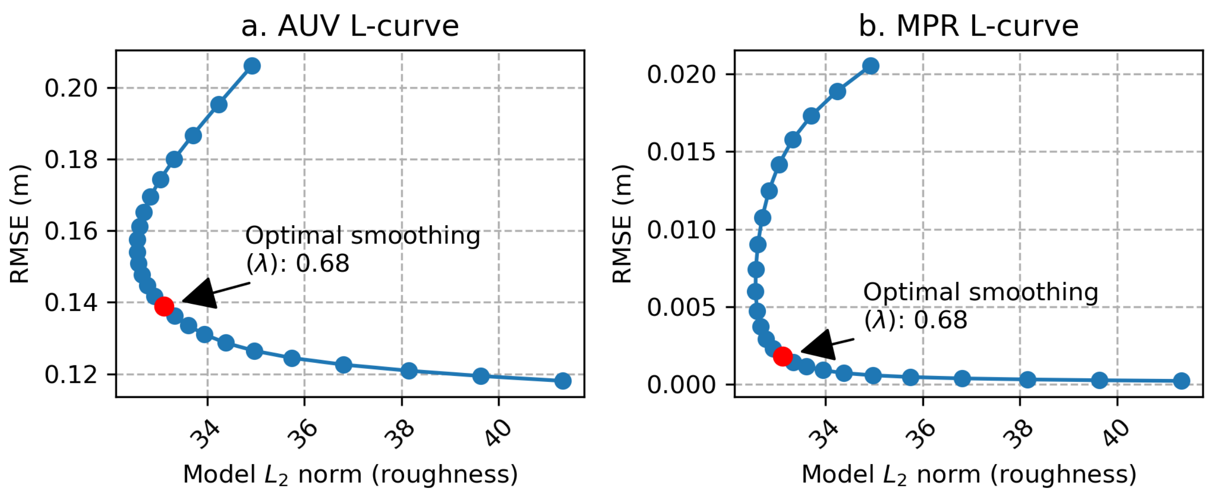

Figure 6. L-curves showing model roughness vs. Root Mean Square Error (RMSE) as a measure of misfit between the model and the data for (a) the AUV data and (b) the MPR data. The optimal smoothness occurs at the corner of the curve. Example shown is for Model 3b.

3.4. Weighing the AUV and MPR data

We weighed the AUV and MPR data on a case-by-case basis for each model due to differences among inversion methods. For Model 1, since the best-fit model was found by a parameter search over uniform pressure values on the MMR surface (all other model parameters were fixed), we calculated the AUV RMSE and MPR RMSE for each iteration then normalized them by dividing each by the maximum RMSE value across all iterations and by the relative uncertainties in the datasets. We then calculated the combined RMSE for each iteration by summing the normalized AUV RMSE and MPR RMSE values. The optimal model was chosen as the model with the lowest combined RMSE value. For Models 2a and 2b, we first weighed the datasets in an MCMC simulation according to their relative uncertainties, then further adjusted the weights over many MCMC simulations to find the weight combination that minimized the combined AUV and MPR RMSE values.

For Models 3a and 3b, we found a tradeoff between the regularization parameter λ and the relative weights, due to higher noise in the AUV data than in the MPR data. Instead of just normalizing the AUV and MPR datasets using their relative uncertainties, we further normalized them by the number of data points in each dataset. The λ value was then chosen as described above in Section 3.3.

4. Results

We found that Model 1 (uniform pressurization of the 3-dimensional MMR) did not fit either the MPR or AUV data well. This was not unexpected, since the MMR geometry is offset from the caldera to the east while the observed deformation is centered on the caldera. Also, the shallowest features along the MMR roof are located beneath the SE part of the caldera and because of this, the model creates the largest surface deformation there, 4-5 km SE of the caldera center (Figures 2, 4a and 6a). This makes sense intuitively since these shallowest MMR features have less overburden and therefore uplift more readily under uniform pressurization. This result tells us that the observed deformation cannot be simply produced by uniform pressure within the entire MMR, which suggests that perhaps the MMR is compartmentalized with isolated melt pockets that are not well connected.

The other four models, which were developed to test the idea of compartmentalization, showed increasing improvement of fit to the MPR data as more parameters were added. The AUV RMSE values were also improved, but not as much and varied from model to model (Table 1). We suspect that this is because of the higher uncertainty associated with the AUV data, which was factored into how the datasets were weighed. To quantify whether the increase in goodness of fit to the data between the models is statistically significant and not due to random fluctuations in the data, we conducted F-tests on each model and its adjacent model with higher complexity using the 95% confidence interval (see Text S2 and Tables S1, S2 in Supplementary Material). We found that the increased goodness of fit to the MPR data across the models is statistically significant. The model pairs for which the AUV RMSE improved with complexity (Model 1 vs. Model 2a, Model 2a vs. Model 2b) also have statistically significant improvement of fit.

Despite differences among model geometries, the models consistently estimated a best-fit volume change of between 0.054-0.060 km^3, except for Model 1 which estimated 0.173 km^3 (Table 1). The best-fit pressure change for Model 1 was 42.4 MPa. Modeled deformation and fit to the MPR data are shown in Figure 7 and AUV repeat bathymetry residuals are shown in

Figure 8. In Models 3a and 3b where pressure was allowed to spatially vary, modeled pressure changes were highest along the western-central edge of the MMR (Figures 4 and 5). There is also a region of positive pressure change in the southern-most southward dipping region of the MMR due to a long wavelength deformation signal present in this area in the AUV data.

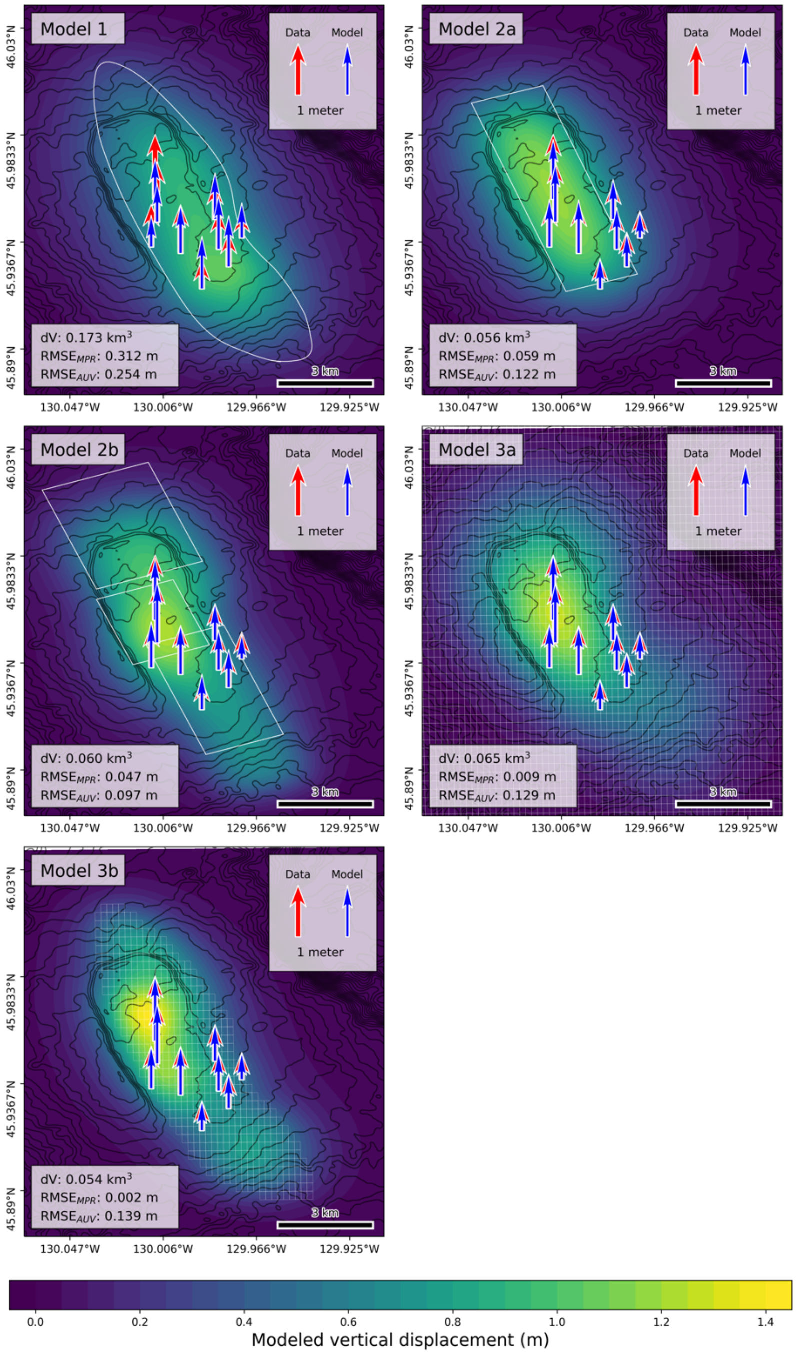

Figure 7. Predicted surface vertical deformation for all best-fit models with comparison between the MPR data (red arrows) and modeled surface displacements (blue arrows). The surface projection of each model geometry is shown as a white outline. Each model's volume change

(dV) and RMSE values between the model and the MPR and AUV data are shown in the lower left corner of each panel.

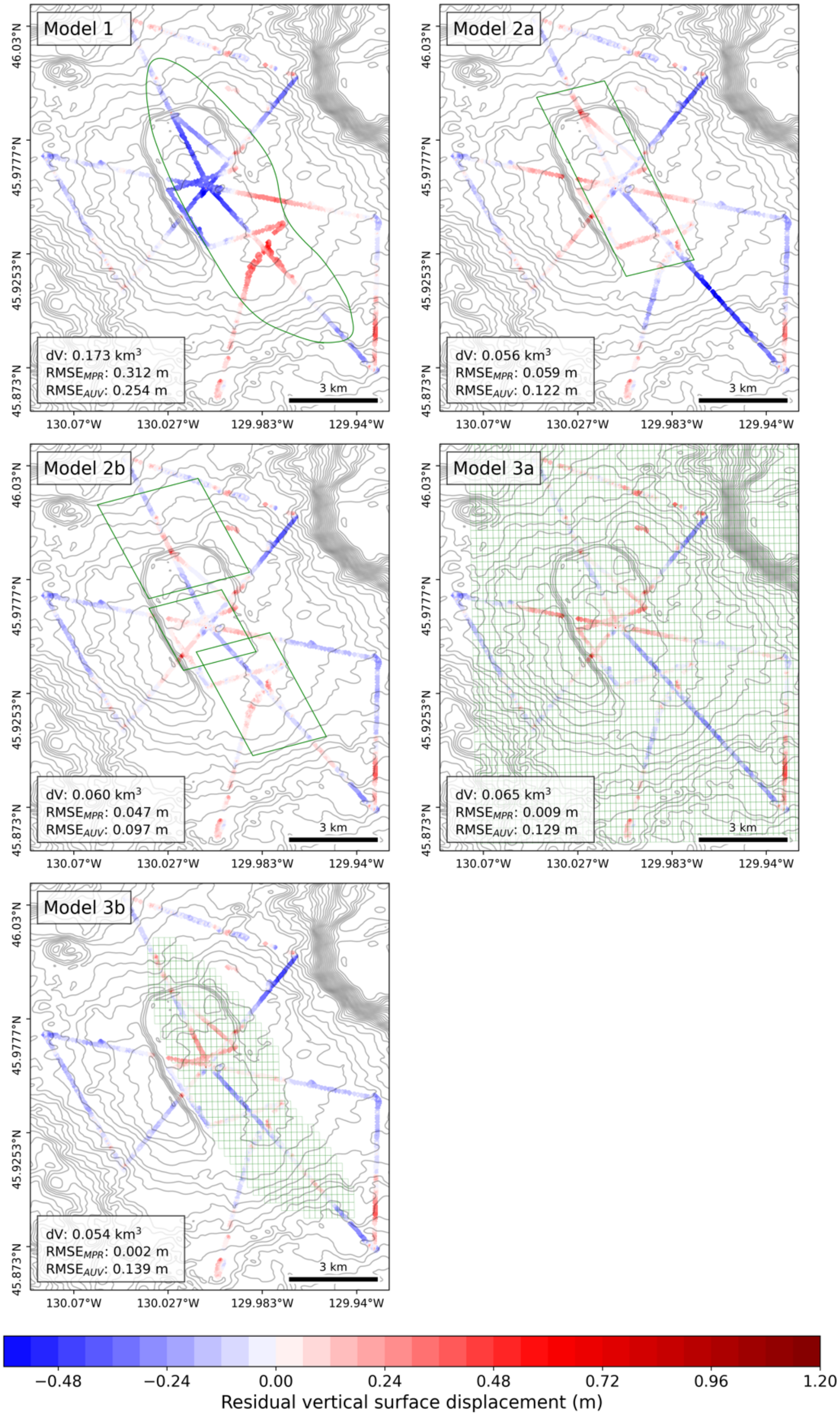

Figure 8. AUV repeat bathymetry residuals plotted by subtracting the modeled displacements from the AUV data. The surface projection of each model geometry is plotted as a green outline.

Each model's volume change (dV) and RMSE values between the model and the MPR and AUV data are shown in the lower left corner of each panel.

5. Discussion

5.1. Model assumptions and limitations

All our models assume homogeneous and isotropic elastic half spaces (except for Model 1, which includes bathymetry). Masterlark (2007) showed that the presence of layered crustal material can increase source depth estimates when compared to models assuming elastic half spaces with uniform properties. Since Axial's volcanic edifice is composed of lava flows emplaced upon one another over time, there is likely some anisotropy in which stiffness is different in the vertical and lateral directions, which could cause an underestimation of source depths. If those layers are dipping, the symmetry of stress around the pressure source would change (Gudmundsson, 2006), which would in turn affect the symmetry of measured ground displacements. Additional vertical anisotropies such as dikes and/or faults would influence the stress and displacement field similarly. However, since we don't have constraints on these potential vertical anisotropies, it is difficult to quantify the effect for our case.

We found in sensitivity testing that inclusion of Axial's bathymetry in a finite element model using a prolate spheroid pressure source fixed at a depth of 3.8 km (the best-fit model of Nooner & Chadwick, 2016) can affect the volume change estimate by up to 27% (Figure S3 in Supplementary Material). This effect would increase with shallower source depths (Williams & Wadge, 1998) such as at the depth of the MMR. This result was unexpected because of Axial's relatively modest bathymetric relief, and more work is needed to better understand which bathymetric features (e.g., caldera walls vs surrounding bathymetric features) influence the expression of vertical deformation for a given pressure source geometry.

Our assumption of elasticity could also affect the modeling results since there may be non-elastic or viscoelastic effects unaccounted for in the models. Numerical modeling implementing viscoelasticity at Mt. Etna has shown that lower pressures can produce the same deformation as elastic models with higher pressure due to viscoelastic relaxation over time (Del Negro et al., 2009). Depending on where this region of viscoelasticity is defined (either above or below the pressure source), this phenomenon could result in either inflation or deflation observed on the surface (Nooner & Chadwick, 2009). Cabaniss et al., 2020 found that non-temperature-dependent elastic rheology requires greater reservoir overpressures to reproduce the observed surface deformation at Axial compared to models that incorporate a temperature-dependent rheology. Additionally, petrological and tomographic studies increasingly show that magma reservoirs are likely composed of discrete melt lenses/sills embedded within a crystal-rich magma mush (Cashman et al., 2017). Magma mush is expected to behave poroelastically or poroviscoelastically (Gudmundsson, 2012; Liao et al., 2018, 2021). Although viscoelastic effects and the presence of magma mush would likely not significantly impact the spatial distribution of modeled pressure changes in our results, it could impact volume change estimates due to magma compressibility. Modeling viscoelastic effects at Axial would be more strongly relevant to the temporal component of the deformation time series, for example to test hypotheses regarding short-term deflation events proposed by Chadwick et al., 2022.

Because of the MMR's relatively shallow depth, modeled surface deformation is sensitive to roof topography variations at the scale of hundreds of meters to kilometers. The reason Model 1 fits the data poorly is because the shallowest features of the MMR roof are located kilometers away from the largest observed deformation (Figure 2). Our argument that the MMR is not pressurized uniformly therefore relies on the assumptions that 1) the MMR morphology has not changed between the 2002 MCS survey and 2016 and 2) the resolution and quality of the MCS results are adequate for our analysis. It is unlikely that the MMR has changed in morphology since the 2002 MCS survey, since preliminary results from a recent 3D MCS survey in 2019 (Axial 3D expedition MGL1905; Arnulf et al., 2019) suggest that the overall shape and main topographic features have not changed. In addition, the deformation pattern has been consistent throughout the history of geodetic monitoring at Axial, despite the eruption in 2015 (Fox 1999; Chadwick et al., 1999, 2006, 2012, 2022; Nooner & Chadwick, 2009, 2016). Uniform pressurization of the MMR might fit the data if the shallowest topographic features were centered beneath the caldera, which would require a change in MMR roof topography of approximately X= 3 km by Y = 6 km by Z = 0.4 km. Therefore, any changes/uncertainties in the MCS results below these dimensions would not alter our conclusions. Changes or uncertainties in the bottom surface topography of the MMR would likely not influence our conclusions, since the displacement at the source for Model 1 (uniform pressurization of the MMR) shows that predicted deformation is not sensitive to these features (Figure 4). This is consistent with findings by Yun et al., 2006, who demonstrated that modeled surface deformation at basaltic calderas is insensitive to the bottom and sides of the model geometry and that it is the upper surface that matters most.

5.2. Seismicity

Seismic activity at Axial associated with the 2015 eruption suggests that pre-eruptive inflation and co-eruptive deflation are partly accommodated by slip on outward-dipping caldera ring faults that extend from the near-surface to ~2 km depth (Wilcock et al., 2016; Waldhauser et al., 2020). Levy et al., 2018 divided the 2015 eruption into 3 phases (pre-, syn-, and post-eruption) and used microearthquakes to estimate the cumulative fault slip for each phase. Hefner et al., 2020 used these slip estimates to subtract fault-induced surface deformation from the observed geodetic data prior to performing model inversions and found that the best-fit prolate spheroid source location was shifted laterally by 2.11 km. This demonstrates that ring fault motion at Axial may contribute to the observed surface deformation during eruptions, but likely only 10% or less.

To compare the observed seismicity to our deformation model results we plotted earthquakes located during our 2016-2020 inter-eruptive study period and seismicity surrounding the 2015 eruption from the Wilcock et al., 2016 & 2017 earthquake catalog in Figure 9. During 2016-2020, seismicity rates started off low (<10 earthquakes per day) for the first 2 years and increased to 10s-100s per day during the next 2 years (Figure 9e), but the amount of expected seismic slip on the ring faults is low, because the magnitude of most earthquakes is also low ($M_W<<2$; Figure 9f).

It is also possible that magma reservoir inflation is accommodated aseismically by the ring faults. The spatial correlation between the observed surface displacements and the caldera could suggest that the ring faults are active. However, there is little evidence of fault slip in the AUV repeat bathymetry data in the form of sharp offsets along AUV track lines where they cross the faults. There may be some slip masked by the uncertainty in the AUV data (±20 cm), but it would still only contribute ~10% or less to the observed uplift.

Regardless of how much of a role the ring faults play in accommodating inflation, it is unlikely that they could accommodate uniform pressurization of the MMR (i.e., Model 1 with ring faults) to produce the observed geodetic data, since most of the surface deformation in Model 1 is to the southeast of the seismicity on the ring faults (Fig. 9a,b). However, if the center of the MMR were pressurized (instead of the west-central edge as in Models 3a and 3b), and the ring faults were allowed to slip, the resulting deformation might fit the geodetic data. An FEM that includes bathymetry, spatially variable pressure, and ring faults that could slip would be most thorough, although the number of free parameters may not be constrainable by the current deformation data. However, recent expansions of the geodetic monitoring network at Axial will be able to better quantify any slip across the caldera faults in the future and will add horizontal displacements.

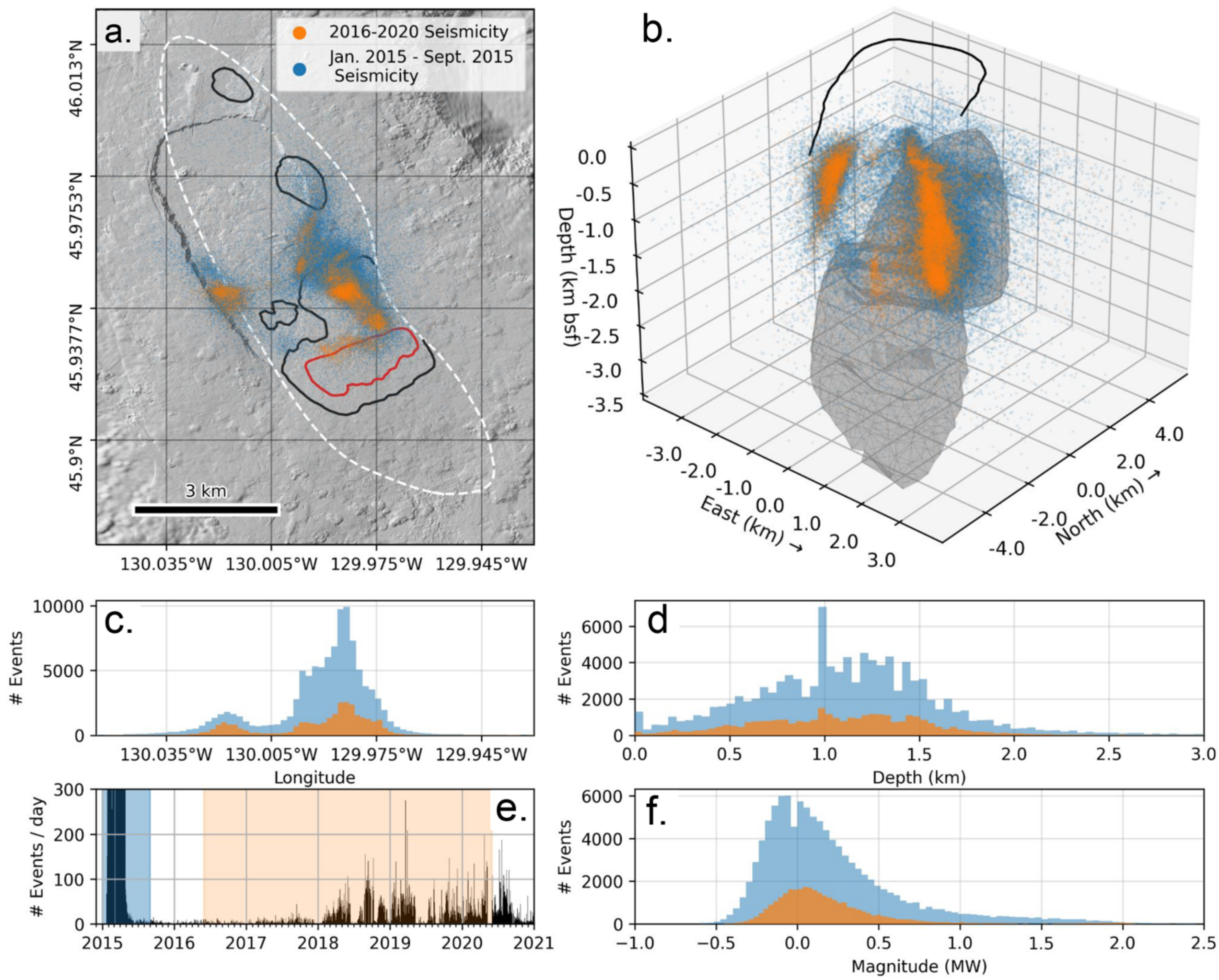

Figure 9. Comparison between seismicity during our study period from 2016-2020 in orange and seismicity associated with the 2015 eruption from January 2015 – September 2015 in blue. Earthquake data is from Wilcock et al. (2016 & 2017) (a) Map view of the caldera bathymetry with the MMR outlined in white. Shallowest parts of the MMR roof are shown with depth contours at -1250m and -1500m (below seafloor) in red and black, respectively. (b) 3-D perspective view of seismicity compared to the MMR geometry (gray mesh) and caldera (black line). (c) Histogram of seismic events along longitude. (d) Shows a histogram of earthquake depths. (e) Time series of seismicity with the 9 months surrounding the 2015 eruption shaded in blue (timespan based on Wilcock et al., 2016) and the 2016-2020 time period shaded in orange. The maximum number of events per day during the 2015 eruption (y-axis upper limit) is ~9000. (f) Histogram of earthquake magnitudes (M_W).

5.3. Implications for magma storage beneath Axial caldera

A best-fitting deformation model cannot reveal the exact geometry of a magma storage system and should not be interpreted as such; rather, a deformation model can provide the approximate location and volume changes of the region(s) where the greatest pressure changes occurred during magmatic activity. While our results provide improved horizontal constraints on where magma accumulates between eruptions, there is inherent non-uniqueness among modeled depths due to the tradeoff between depth and pressure. While our best-fit horizontal sill (Model 2a) is similar in horizontal geometry to the best-fit horizontal sill found by Hefner et al. (2021), the depth of our sill is deeper at 2.7 km compared to 0.97-1.24 km, which is likely due to differences in inversion methods and/or the tradeoff between depth and pressure.

Despite this tradeoff, the consistent volume change estimates of 0.054-0.060 km^3 among Models 2a-3b suggests that the volume change is not significantly sensitive to model depths within the depth range of the MMR. In addition, we tested an FEM model using the prolate spheroid geometry (the best-fit solution from Nooner & Chadwick, 2016) constrained only by the 2015-2020 MPR data, which resulted in a volume change of 0.077 km^3 (Figure S3a in Supplementary Material). Since this included an extra year's worth of inflation compared to the 2016-2020 models we show in this study, the estimated volume change for the 2016-2020 time period would be expected to be somewhat lower, more or less consistent with the volume change estimates using geometries constrained by the MMR in Table 1. This demonstrates that the estimated volume change for this inter-eruptive recharge period is not highly sensitive to model geometry, depth, or location.

The total volume of the shallow magma storage system beneath Axial was estimated by Arnulf et al., 2014 to be 18-30 km^3 and the modeled co-eruptive volume change associated with previous eruptions has been estimated to vary between 0.147 – 0.206 km^3 using analytical model source depths of 3-3.8 km (Chadwick et al., 1999, 2012; Hefner et al., 2020; Nooner & Chadwick, 2016). Our study models the observed inflation from 2016-2020, during a time when the magma supply rate was initially high, but then waned with time following the 2015 eruption (Chadwick et al., 2022). Given that the magma supply rate is estimated to have varied from >0.1 km^3/year to <0.01 km^3/year during that time period (Chadwick et al., 2022), our volume change estimates are reasonable.

Mullet & Segall (2022) demonstrated that as the melt fraction of a mushy magma reservoir increases, the deformation caused by a mush-dominated magma storage system is increasingly driven by the overall shape of the mush body, instead of any pressurized melt lens within the mush. If the melt fraction within the MMR is high enough to cause Axial's deformation to be driven by the entire mushy body (instead of individual sills) and if we assume that the MMR is a continuous body, it follows that using the MMR geometry as a pressure source should fit the deformation data. The poor fit to the data of Model 1 as well as the pattern of pressure distribution in Models 2b, 3a and 3b are instead suggestive of compartmentalization of melt within the MMR and a relatively low melt fraction in the surrounding mush (Figure 10). In this context, compartmentalization means that melt bodies within the MMR are not connected hydraulically, at least on time scales that are relevant to the deformation cycle at Axial.

Based on the correlation between the modeled spatial pressure distribution in our models and the MMR outline (the correlation is most apparent in Model 3a), another possibility is an intermediate hypothesis in which one primary sill is pressurized and a large mushy region surrounding the sill that loosely approximates the MMR extent is also pressurized but to a much lesser degree. Both possibilities conflict with melt fraction estimates within the MMR by Arnulf et al., 2018, which suggest that the highest melt fraction is directly beneath the shallowest MMR roof features southeast of the caldera center, with relatively low melt fraction elsewhere.

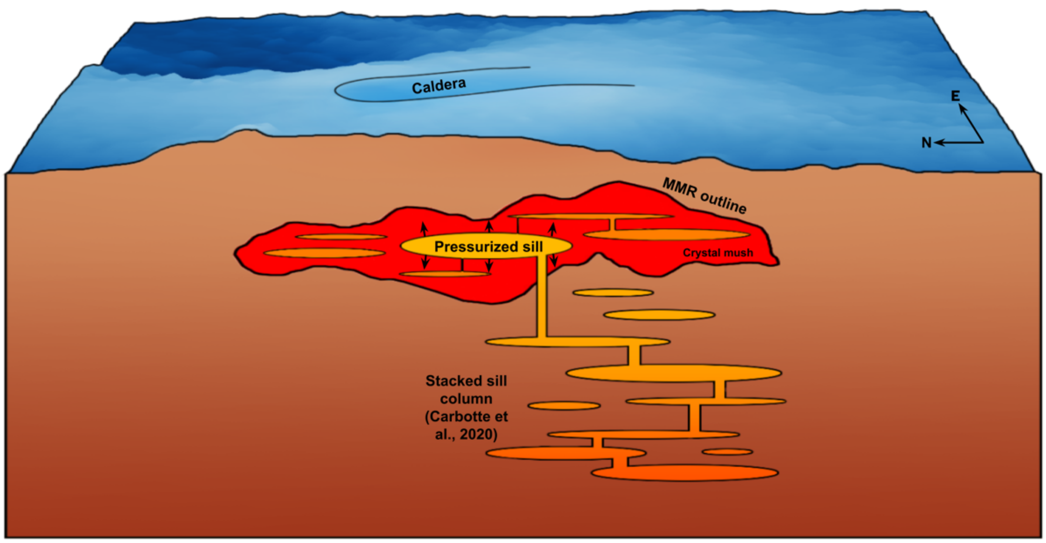

Figure 10. Schematic diagram illustrating possible compartmentalized melt distribution in which sills are emplaced in crystal mush both within and below the MMR at Axial Seamount.

The depth of magma residence estimated by petrological analyses (Dreyer et al., 2013) is deeper at 3-6 km than the MMR depth range of 1.1-2.8 km, but is consistent with the deeper system of stacked sills beneath the MMR imaged by Carbotte et al., 2020 extending from 3-5 km depth below seafloor. Since we did not consider deformation sources in this depth range, we cannot rule out contribution to the deformation field of a potential pressure source (or multiple sources) in the deeper stacked sill region. Non-uniqueness among models due to the tradeoff between depth/pressure would likely hinder efforts to resolve pressurization of multiple vertically stacked sills or the combination of compartmentalized MMR pressurization with a source representing the stacked sill region. However, since the stacked sills are exclusively beneath the SSE part of the caldera, they probably cannot produce the observed caldera-centered deformation by themselves.

The concept of a "magma domain" was applied to Axial Seamount by Sigmundsson 2016 to describe a crustal volume that hosts magma at a shallow level with varying amounts of melt/mush and pockets with variable connectivity. This concept was also applied to the

Bárðarbunga volcanic system in Iceland where caldera collapse in 2014-2015 was modeled using a sill-like magma body within a larger magma domain, which supplied magma to a lateral dike (Sigmundsson et al., 2020). Along with these studies, our results have implications for how deformation models constrained by geodetic data alone should be interpreted, since a best-fit pressure source is likely not representative of the full extent of magma storage beneath a volcano. Although petrological studies suggesting that magma reservoirs are composed of a complex network of melt sills embedded in crystal mush have primarily focused on mafic volcanoes, there is increasing evidence that this may also be the case for some silicic systems (Cashman & Giordano, 2014).

6. Conclusions

The ability to accurately forecast volcanic eruptions is an important goal in hazard mitigation research. Linking precursory signals like ground deformation to subsurface processes is therefore essential. With the increase in spatial coverage of Axial's deformation monitoring due to the application of AUV repeat bathymetric surveys, there is now adequate data to justify more complex deformation modeling than what has been done previously. We constructed a suite of numerical and analytical models geometrically constrained by the shape of the seismically imaged MMR to investigate the role of the MMR in creating the observed surface deformation and to test the hypothesis that the MMR is compartmentalized. Although our estimated volume change of 0.054-0.060 km^3 for the inflation period between 2016-2020 is reasonable considering previous estimates of inflation, deflation, and eruption volumes, the models make assumptions (flat seafloor, full elasticity, no ring faults) that could influence the volume change and/or depth estimates. Nevertheless, the models with spatially varying pressure (Models 3a and 3b) suggest that magma accumulates during Axial's inter-eruptive recharge periods along the western-central edge of the MMR with some potential additional accumulation in the southern-most southward dipping region of the MMR. Future modeling efforts with additional complexity and more parameters will likely require increased data constraints in the form of higher resolution seismic imagery, AUV repeat bathymetry with lower uncertainty, and/or the additional constraint of horizontal deformation measurements.

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Open Research

The code and data used for this research can be found at https://zenodo.org/records/10785669 (Slead, 2024). Academic licensing for Abaqus software is provided by Simulia, Dassault Systèmes. The VSM software used for analytical modeling can be found at https://github.com/EliTras/VSM (Trasatti, 2022).

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