

MagmaEst

**Improving MAGMA source parameter ESTimates at Svartsengi based on Finite
Element ground deformation models**

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1 Ágrip

Bættur skilningur á kvikukerfum í virkum eldfjöllum er mikilvægur; bæði fyrir hættumat og til að skilja hitagjafa jarðhitakerfa. Þar sem ekki er hægt að skoða innviði eldfjalla beint, eru jarðskorpuhryefingar mikilvæg aðferð til að kanna kvikukerfi þeirra. Of einfaldar forsendur í líkönum, t.d. varðandi breytileika í eðliseiginleikum jarðskorpuunnar, geta haft umtalsverð áhrif á niðurstöður. Í þessu samhengi er gott að nota reiknilíkon t.d. bútalíkon, sem geta tekið tillit til breytileika í gerð jarðskorpuunnar og óreglulega forma kvikusvæða.

Níu eldgos hafa þegar átt sér stað við Svartsengi síðan árið 2023. Mælt landris og landsig á þessu tímabili má tengja beint við kvikuhreyfingar undir Svartsengi. Hingað til hafa líkön af jarðskorpuhreyfingum í Svartsengi ekki tekið tillit til breytilegra eðliseiginleika jarðskorpuunnar.

Við settum upp þrívið bútalíkon af jarðskorpuhreyfingum við Svartsengi sem innihalda breytilegra fjaðurstuðla sem voru reiknaðir út frá hraða jarðskjálftabylgna og einfaldra líkana af eðlismassa. Við breyttum gildum á borð við dýpi og þrýstingsbreytingar kvikusvæðisins til að finna minnsta mismun milli líkana og mælinga á jarðskorpuhreyfingum frá júní—ágúst 2024. Kvikuhólfín sem við könnuðum voru kúlur og sporvölur. Mismunurinn er minnst fyrir þríasa sporvölu sem er á 5.25 km dýpi, stefnir í átt N60°E, hallar 10° til norðvestsurs og er með 27.5 MPa þrýstibreytingu. Þessi sporvala var með grynnssta dýpi af þeim sem við könnuðum og pössuðu við mæligögnin. Okkar líkön sýna öll 1.5—1.9 km meira dýpi en líkön sem nota einsleit gildi fjaðurstuðla. Þessar niðurstöður sýnir að það sé mikilvægt að taka tillit til breytileika í rúmi í fjaðureiginleikum jarðskorpuunnar.

2 Abstract

Detailed understanding of the magmatic plumbing system of active volcanoes is important for both hazard assessment and for understanding the heat source of overlying high-temperature geothermal systems. Since it is not possible to directly observe the interior of active volcanic systems, ground deformation models are valuable tools to constrain subsurface magmatic processes. This can be partially mitigated by using numerical models, which can incorporate spatially variable material properties and shapes.

The Svartsengi volcanic system, located on the Reykjanes Peninsula, SW-Iceland, has experienced a series of volcanic eruptions and associated in- and deflation cycles of a midcrustal magmatic reservoir. Despite this, to date there is no deformation model of the Svartsengi magmatic system, which considers crustal heterogeneity.

We implemented a series of three dimensional, elastic Finite Element deformation models of the Svartsengi volcanic system, which consider crustal heterogeneity by deriving elastic properties from seismic velocity and density models. Using forward models, we varied source parameters systematically to find the best-fitting vertical source location, orientation, and pressure change for spherical sources as well as for a prolate and a triaxial ellipsoid. We find that a triaxial ellipsoid which has the shortest axis in a sub-vertical direction, located at central depth of 5.25 km, with a strike of 60°, a dip of 10° towards northwest and a pressure change of 27.5 MPa best reproduces geodetic observations made during an inter-eruptive inflation episode from June–August 2024. This geometry required the shallowest central depth out of the models tested here. The best-fitting source depths we found were overall shifted towards larger depths by 1.5–1.9 km compared to previous analytical models which assume uniform host rock. This demonstrates the importance of considering crustal heterogeneity in models of surface deformation.

3 Introduction

Many volcanic systems host magma reservoirs in the mid- to upper crust, which can contain variable proportions of liquid melt and crystal mush. For individual systems, constraints on the location of these magma reservoirs are crucial for both hazard assessment and their role as heat sources to overlying geothermal systems (Sigmundsson et al., 2024; Scott et al., 2015; Burchardt et al., 2022). Geodetic observations and models of surface deformation are important tools used worldwide to infer and quantify subsurface magmatic movements (e.g., Amelung et al., 2000; Montgomery-Brown et al., 2010; Sigmundsson et al., 2015; Hickey et al., 2016; Gottsmann et al., 2020; Aloisi et al., 2020; Sigmundsson et al., 2022).

Models of ground deformation can be broadly grouped into analytical and numerical models. Analytical models assume strongly simplified source geometries and typically uniform properties of the crust, which makes them fast and computationally efficient, even if running up to or more than one million iterations in inversions (Battaglia et al., 2013; Bagnardi and Hooper, 2018). This makes them valuable tools for monitoring, where time is often a critical factor. However, the same simplifications that allow for computational efficiency can bias the estimated source parameters by oversimplifying the shape of the source and the structure of the Earth's crust (Masterlark, 2007; Poppe et al., 2024).

Numerical models can incorporate spatially variable material properties, different rheologies and boundary conditions and more geometrically complex shapes e.g., for the deformation source and for surface topography (Currenti et al., 2008; Trasatti et al., 2005; Masterlark, 2007; Hickey et al., 2015; Gottsmann et al., 2020; Greiner et al., 2025). However, these come at the cost of significantly higher computational resources and times, requiring modified procedures compared to inversion schemes commonly used for analytical models (Masterlark, 2007; Currenti et al., 2010; Hickey et al., 2015; Gottsmann et al., 2020; O'Hara, 2023). It is well known, that for most source geometries, the consideration of crustal heterogeneity tends to increase the source depth, but the effect is variable depending on the individual volcanic system in question (Trasatti et al., 2005; Masterlark, 2007; O'Hara, 2023; Greiner and Geirsson, 2024). Mismatches in depth estimates are commonly observed between geodetically derived values and those from thermobarometrically analyzed eruptive products, with the former typically suggesting shallower sources (Trasatti et al., 2005; Haddadi et al., 2017; Matthews et al., 2024; Greiner and Geirsson, 2024). While this discrepancy may partially reflect equilibrium conditions different from the uppermost magma reservoir, which is typically reflected in geodetic estimates, the shift to slightly larger depths from considering crustal heterogeneity can improve the agreement between the different methods.

The Svartsengi volcanic system is part of the Reykjanes Peninsula, an obliquely spreading segment of the Mid-Atlantic Ridge in SW-Iceland. Svartsengi has experienced an as of September 2026 ongoing series of volcanic eruptions since late 2023 (e.g., Sigmundsson et al., 2024; Matthews et al., 2024). These eruptions are fed from a mid-crustal magma reservoir, which consistently alternates between co-eruptive or co-diking deflation and intereruptive inflation, which is mainly attributed to the removal and addition of magma, respectively (Parks et al., 2025; Lanzi et al., 2026). Analytical models of the 2023-2025 eruptive episodes locate the magma reservoir at approximately 3 – 5.5 km depending on the source geometry, with point-sources being the deepest and sill-like or ellipsoidal sources being shallower (Sigmundsson et al., 2024; Parks et al., 2025; Lanzi et al., 2026). Thermobarometric estimates based on erupted lavas suggest somewhat deeper storage depth of 4 – 7 km (Matthews et al., 2024; Caracciolo et al., 2023).

This study aims to better reconcile the discrepancy between geodetic and petrological depth estimates by explicitly accounting for crustal heterogeneity based on seismic velocity models. Using the Finite-Element (FE) method we aim for better constraints on the depth and shape of the Svartsengi magma reservoir based on surface deformation observed with the local geodetic network.

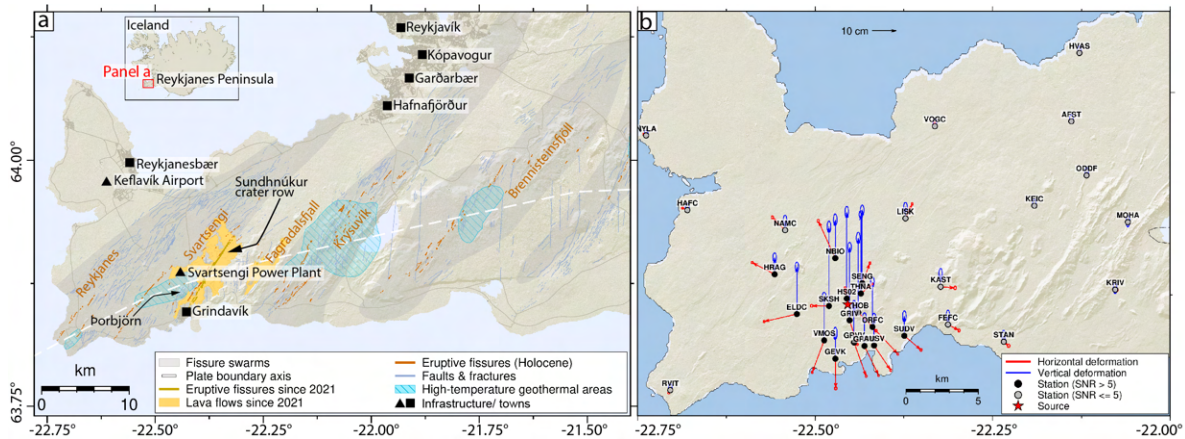


Figure 1: a) Map of the Reykjanes Peninsula in SW Iceland. Fissure swarms by Jóhannesson and Sæmundsson (2009). Plate boundary axis by Michalczevska et al. (2014). Faults and fractures were mapped by Clifton and Kattenhorn (2006). Holocene eruptive fissures/crater rows and geothermal areas: Náttúrufræðistofnun Íslands, 2014. Lava flows and fissures since 2021: Pedersen et al. (2022), Belart et al. (2023), Gunnarson et al. (2023), and Parks et al. (2025). Digital elevation model: Landmælingar Íslands, 2024. b) Observed surface deformation during the inflation episode from 5 June – 21 August 2024 recorded with continuous GNSS stations. Data from Lanzi et al. (2026). The colour of the dots at each station marks whether the signal-to-noise ratio (SNR) of the vertical displacement component is above or below 5, respectively.

4 Background

The Svartsengi volcanic system is located on the Reykjanes Peninsula in SW-Iceland (Figure 1a). The Reykjanes Peninsula is an oblique segment of the divergent mid-Atlantic Ridge and marks the transition of submarine spreading on the Reykjanes Ridge to subaerial rift zones that cross Iceland approximately from SW to NE (e.g., Einarsson, 2008; Sigmundsson et al., 2020a).

Volcanic systems on the Reykjanes Peninsula are characterized primarily by fissure swarms, which are arranged en-echelon along the plate boundary axis and consist of normal faults, old eruptive fissures and crater rows. Well-developed central volcanoes are absent. Instead, most systems host at least one high-temperature geothermal area at the intersections of the fissure swarms with the plate boundary, which runs along the peninsula at approximately $N70^{\circ}E$. Volcanism on the peninsula is highly episodic, alternating between periods of frequent volcanic activity that last for ca. 200–400 years and intervals of volcanic quiescence with an approximate duration of 800–1000 years (Sæmundsson et al., 2020; Einarsson, 2008).

The Svartsengi volcanic system has experienced an ongoing rifting episode since the fall of 2023 with nine eruptions and two additional dike intrusions as of September 2026 (Icelandic Meteorological Office, 2025). A dense monitoring network of continuously recording GNSS stations (Global Navigation Satellite System), complemented by Interferometric SAR Synthetic Aperture Radar (InSAR) records ground deformation in the area. In addition to plate motion and long-term subsidence due to exploitation of the high-temperature geothermal system, surface deformation associated with magma movements has been observed there since 2020 (Vadon and Sigmundsson, 1997; de Freitas, 2018; Cubuk-Sabuncu et al., 2021; Sigmundsson et al., 2024). These are characterized by repeated inflation episodes caused by magma accumulation at depth and deflation during dike intrusions and eruptions (Sigmundsson et al., 2024; Parks et al., 2025).

Since 2020, deformation associated with in- and deflation of the magmatic reservoir is centered

just west of Mt. Þorbjörn. Geodetically derived estimates for the depth of the magma reservoir range between 3.5–4.5 km for spherical sources, 4–5.5 km for a subhorizontal, elongated sill, and 3–3.5 km for prolate ellipsoids (Geirsson et al., 2020; Sigmundsson et al., 2024; Parks et al., 2025; Lanzi et al., 2026). Since March 2024, inflation-derived source depths appear to have stabilized at 3.9 ± 0.2 km, 3 ± 0.2 km and 4.7 ± 0.1 km for spherical, ellipsoidal and sill-shaped sources, respectively (Lanzi et al., 2026). An inversion based on shape-optimization found a depth range of 6–8 km for a flat, elongated and dipping source (Perrot et al., 2026). However, in this study, Svartsengi was a case study for a proof of concept to the shape optimization being applied to invert for ground deformation sources. The model domain was too small to avoid edge effects, which is very likely to have affected both the source shape and the estimated source location including its depth. Storage depths from thermobarometry of lavas erupted between December 2023–May 2024 range from 4–7 km, which is somewhat deeper than most geodetically derived estimates (Matthews et al., 2024). Seismic tomography studies have found anomalies underneath Svartsengi, which have been interpreted as the magma domain and the overlying geothermal area (Rahimi Dalkhani et al., 2024; Jenkins et al., 2025; Allas et al., 2026).

5 Methods

To evaluate the effect of heterogeneous elastic subsurface structure on surface deformation, a series of forward deformation models were implemented using the Finite Element method. Model parameters were systematically altered for three different source geometries to reduce the residual between the predicted surface deformation and geodetic observations from GNSS stations at Svartsengi in the summer of 2024. To decouple the interplay between changing the source depth and the pressure change, we analyzed not only the direct surface displacement at GNSS stations, but also the ratio of horizontal to vertical displacement at these points, which is only affected by the depth, but not by the pressure change.

5.1 Geodetic Data

Model results are compared to surface deformation data, which was recorded by an extensive network of continuous GNSS stations (Global Navigation Satellite System) that is operated by the Icelandic Meteorological Office (IMO) and the University of Iceland (Figure 1b). The time frame considered in this study spans 5 June – 21 August 2024, which corresponds to the time between the end of the May 2024- and the beginning of the August 2024 eruptions. The time frame and data is similar to that inverted by Parks et al. (2025) using an Okada-like sill and a Mogi-point source, and we refer to their study for details on the data processing. The data was provided by the Icelandic Meteorological Office and is the same as was used by Lanzi et al. (2026). Considering intereruptive inflation episodes is preferable for modelling of the magma reservoir, since the co-eruptive deflation signal is superimposed onto deformation related to diking and potential near-surface fracture movements (Parks et al., 2025; Wire et al., 2024). Lanzi et al. (2026) furthermore found that the location of the deformation source has been stable since May 2024, suggesting that the selected episode can be considered to be representative of the stage of the magmatic system since 2024. We excluded all GNSS stations from further analysis that showed a vertical displacement less than 5 times their uncertainties to reduce the influence of noisy stations with small signals (Figure 1b).

5.2 Model Setup

The Finite Element method (FEM) numerically solves differential equations and has been applied to simulate volcano deformation for a few decades due to its capability to incorporate complex geometries and spatially varying material properties (Dieterich and Decker, 1975; Trasatti et al., 2005; Gottsmann

et al., 2020; Greiner and Geirsson, 2024). All models in this study were implemented using COMSOL Multiphysics version 6.1. Further analysis was done in Python.

The model domain assumed a linearly elastic rheology with a Young’s modulus of 88.454 GPa and a Poisson’s ratio of 0.2606. Its horizontal dimensions were 100 km x 100 km and it covered 100 km in the vertical direction with the top surface at 0 km. All lateral sides consisted of a 10 km-wide layer that used an Infinite Element domain, which stretches the coordinates to approximate an unbounded half-space (Hickey and Gottsmann, 2014). The lateral boundaries of the model domain were set to a roller-boundary condition, allowing for only boundary-parallel motion, and the bottom boundary was kept fixed. The domain surface was free to move and the deformation source was represented by a uniformly pressurized cavity. All representations of the magma reservoir were centered slightly west of Mt. Þorbjörn (see e.g. Figure 1b) at 63.869° N, -22.454° E, which is the location found by Parks et al. (2025). The model domain was represented by a tetrahedral mesh with variable resolution. The maximum element size was finest at the surface near GNSS sites (50 m) and at the deformation source, but gradually increased further away.

We implemented three different geometries to represent the magma domain: a sphere ($a = b = c$), a prolate ellipsoid ($a > b = c$) and a triaxial ellipsoid ($a > b > c$). The sphere and the prolate ellipsoid were first implemented in a uniform, flat-topped model domain and compared to equivalent analytical solutions (Mogi, 1958; Yang et al., 1988). This benchmarking is done to ensure that the model setup and numerical aspects, such as the mesh resolution, domain size, and boundary conditions do not bias the predicted surface displacements (Hickey and Gottsmann, 2014). Analytical solutions used the open source Python code from the Volcanic and seismic source Modeling toolbox by Trasatti (2022). For the triaxial ellipsoid, there is no corresponding analytical solution to benchmark against. However, the only difference between it and the prolate ellipsoid was to change the value for the vertical semi-axis c , therefore we assume that successful benchmarking of the prolate ellipsoid against the Yang-model also covers the triaxial ellipsoid. For benchmarking of the spherical source against a Mogi model, a cavity with a radius of 500 m was placed at a central depth of 4 km and subjected to a boundary load of 1295 MPa (Mogi, 1958). The prolate ellipsoid, which measured $a = 4$ km in its long axis and $b = c = 1.5$ km in its short axis was placed at 6 km depth. The long axis points north-east with an azimuth of 58.16° and it was subject to a pressure change of 25 MPa. Discrepancies between the numerical and analytical models are reported in Table 1 and are sufficiently small to consider the benchmarking successful.

A three-dimensional model with varying elastic properties of the crust was derived from seismic velocity model for p- and s-wave velocities from Allas et al. (2026) and a depth-dependent density model adapted from Sigmundsson et al. (2020b). The seismic velocity model has a resolution of 500 m in all directions and stretches over ca. 30 km along the peninsula, covering the area from Svartsengi to Krýsuvík with a depth down to ca. 15 km (Figure 2). The density model is a one dimensional model

Table 1: *Maximum displacement of the spherical and ellipsoidal FEM-models, maximum residual to the respective analytical models and root-mean-square value (RMS) for each displacement component during benchmarking.*

Geometry	Component	Max. displacement [mm]	Max. residual [mm]	RMS [mm]
Sphere	E-W	83.43	2.83	0.60
	N-S	82.89	2.75	0.60
	Vertical	213.32	3.47	0.32
Prol. ellipsoid	E-W	56.75	2.12	0.67
	N-S	64.93	2.56	0.75
	Vertical	171.32	7.57	2.39

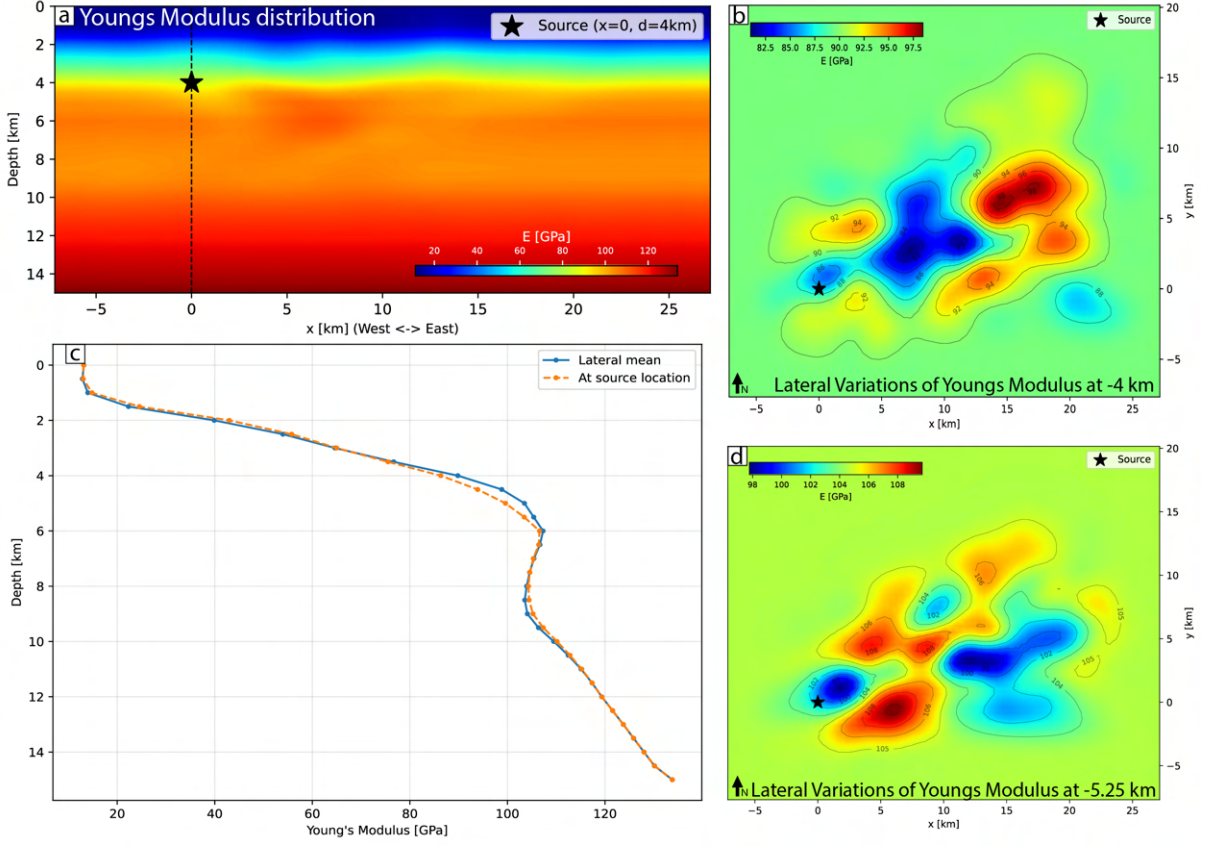


Figure 2: a) East-West oriented cross-section through the heterogeneous elastic subsurface model for the Reykjanes Peninsula derived from 3D seismic velocity models and a 1D-density model (Allas et al., 2026; Sigmundsson et al., 2020b). The black star and black dashed line marks the center of inflation at Svartsengi. b) and d) Horizontal crosssections through the heterogeneous model at 4 km depth (approximate center of inflation found by Parks et al., 2025) and at 5.25 km depth, respectively. c) Depth-dependent comparison of the lateral mean Young's modulus and of the modulus at the center of inflation.

and reaches from the surface down to ~ 16 km depth with uneven spaces in between data points. In any part that is not directly covered by these models, the values were extrapolated as constant. Based on the seismic velocities v_p and v_s and the density ρ the Young's modulus and Poisson's ratio were obtained using

$$E = \rho v_s^2 \frac{3v_p^2 - 4v_s^2}{v_p^2 - v_s^2} \quad (1)$$

$$\nu = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)} \quad (2)$$

The three different geometries (sphere, prolate and triaxial ellipsoids) were inserted into the heterogeneous elastic model. While keeping the sources centered at 63.869° N, -22.454° E (Parks et al., 2025), consistent with the center of uplift, the depth, pressure and where applicable strike and dip of the sources were varied systematically (Table 2). Three different radii were tested for the spherical source. The dimensions of the prolate ellipsoid are based on estimates used by Sigmundsson et al. (2024) and the triaxial ellipsoid is a modification of that geometry to approximate a more sill-shaped reservoir.

In uniform elastic models, for a given geometry the elastic stiffness of the crust and the pressure/volume change experienced by the deformation source only affect the amplitude of the displacement vector at any given point, but not its direction. The ratio of horizontal to vertical displacement at any point only changes with the source depth. Similarly, the source depth is the primary control on this ratio in a heterogeneous elastic model (Greiner and Geirsson, 2024). This effectively decouples the parameter-dependencies of the source depth and pressure if the dimensions of the source remain constant and can be constrained externally, e.g., from other sources of data. Using forward modeling, successive parameter sweeps were conducted and the model results then compared to the geodetic data. A first sweep over the source depth was used to find the smallest residual between the modeled and observed ratio of horizontal to vertical displacement by determining the Root Mean Square error (RMS). Once the depth was established, a second sweep was run over a range of pressures to match the deformation amplitude. For the ellipsoids, the strike was determined by comparing the azimuth of the horizontal deformation against the observed azimuth. For the triaxial ellipsoid, the dip along the short horizontal semiaxis (rotation around the long axis) was included in two two-dimensional sweeps. First, depth and dip were varied together and compared using the RMS of the deformation ratio. The dip only had a small influence on the ratio with almost identical RMS over a wide range of different angles (Figure 8a). Because of that, a second two-dimensional sweep over pressure and dip was used to find the best fitting pressure- dip-combination based on the amplitude as both parameters influence the absolute horizontal and vertical displacement.

The ranges of explored parameter are listed for each geometry in Table 2. The step size during sweeps was 250 m and 50 m for the depth, 2.5 MPa and 5 MPa for the pressure, 0.1° , 1° , 2° and 5° for the strike and 2.5° and 5° for the dip. The best-fitting model was determined based on the RMS of the individual displacement components. For this, we only considered stations with a signal-to-noise-ratio of $SNR > 5$ (Figure 1b).

5.3 Limitations

Like all models, those implemented in the current study have to make a number of simplifying assumptions. We assume a linearly elastic rheology. While the crustal heterogeneity derived from the seismic velocities captures large-scale variations and is in this regard an improvement compared to uniform models, the model does not consider inelastic processes, such as viscoelastic or plastic deformation, which in the presence of a well-established magma reservoir are likely to take place and affect deformation to some degree (e.g., Hickey et al., 2015; Li et al., 2021). However, on the relatively short timescales of a few weeks considered in the present study, we assume that viscoelastic effects are negligible. Due to the resolution limit associated with km-scale wavelengths, seismic tomography does not capture small-scale structures very well (Lees, 2007). However, larger features such as the low-velocity anomaly in the vicinity of the magma reservoir are well resolved and are likely more relevant for the present study.

Table 2: *List of models and associated deformation sources which were compared to the observed GNSS data with consideration of a heterogeneous elastic subsurface structure. a, b, and c are the half-axes of ellipses (corresponding to the radius for a sphere). All models were horizontally centered at 63.869° N, -22.454° E Parks et al. (2025).*

Model	Geometry	a [m]	b [m]	c [m]	Depth [km]	Pressure [MPa]	strike [$^\circ$]	dip [$^\circ$]
S1	sphere	1000	1000	1000	4 - 7	1 - 400	-	-
S2	sphere	1500	1500	1500	5 - 6	10 - 100	-	-
S3	sphere	2000	2000	2000	5 - 6	10 - 100	-	-
PE	prolate ellipsoid	4000	1500	1500	4 - 6	10 - 100	40 - 90	0
TE	triaxial ellipsoid	4000	1500	500	4 - 6	10 - 30	50 - 80	30 - 50

Table 3: *Parameters of the best-fitting models among those tested in the parametric sweeps. Entries marked "—" indicate that the parameter is not applicable or was not varied. For model TE, note that the negative dip relates to that the strike was only varied between $N0^\circ E$ and $N180^\circ E$. Geometrically, the southeastern edge of the source is slightly higher than the northwestern one and the axis of rotation coincided with the major semi-axis a . The volume change was derived as the surface integral of the deformation over the reservoir boundary.*

Model	Depth [km]	Pressure [MPa]	Strike [°]	Dip [°]	Volume change [m^3]
S1	-5.75	330	—	—	$26 \cdot 10^6$
S2	-5.75	90	—	—	$25 \cdot 10^6$
S3	-5.80	35	—	—	$25 \cdot 10^6$
PE	-5.50	25	60	—	$21 \cdot 10^6$
TE	-5.25	27.5	60	-10	$18 \cdot 10^6$

Table 4: *Root-mean-square values for East-West, North-South and vertical displacement components for comparison between the GNSS data by Lanzi et al. (2026) and the five model geometries tested here (see Table 2 for geometries and Table 3 for parameters which were varied). The calculation of the RMS considered only GNSS stations with a signal-to-noise ratio > 5 .*

Model	RMS_{EW} [mm]	RMS_{NS} [mm]	RMS_{vert} [mm]
S1	25.4	16.8	36.8
S2	24.2	15.8	36.2
S3	24.1	15.5	33.4
PE	16.2	17.7	31.5
TE	10.8	13.5	9.3

It is well known that elastic deformation models of magmatic systems tend to require unrealistically high pressure changes, which exceed common estimates of the host rock’s tensile and shear strength (Schultz, 1995; Currenti and Williams, 2014; Greiner and Geirsson, 2024). Both a larger source volume and considerations of inelastic deformation are known to reduce pressure changes (Trasatti et al., 2005; Hickey et al., 2015).

This study implemented forward models only and constraints on the source location were derived from parameter sweeps, using the decoupling of pressure and depth through the ratio of horizontal to vertical displacement. For spherical sources this works well, but is more challenging for sources with a higher degree of asymmetry such as elliptical sources, where there are additional geometrical parameters. We accounted for those by sweeping over the depth and pressure first and only then varying strike and dip, which we assume are secondary controls. Furthermore, the risk of falling into local minima likely grows with the number of successive parameter sweeps, which can in the present study be mitigated by comparison to the results of the analytical models and inversions by Parks et al. (2025). Nonetheless, future works should consider FEM-based inversions and should also consider InSAR-data as an additional data set to compare to.

6 Results

6.1 Sphere

The best-fitting models found through parametric sweeps for spherical sources (S1–S3) have a central depth of 5.75–5.8 km and pressure changes of 35–330 MPa (Figure 3a–d, and result in a volume change of $25 \cdot 10^6 - 26 \cdot 10^6 m^3$ (Table 3). Increasing the source radius not only decreased the pressure due

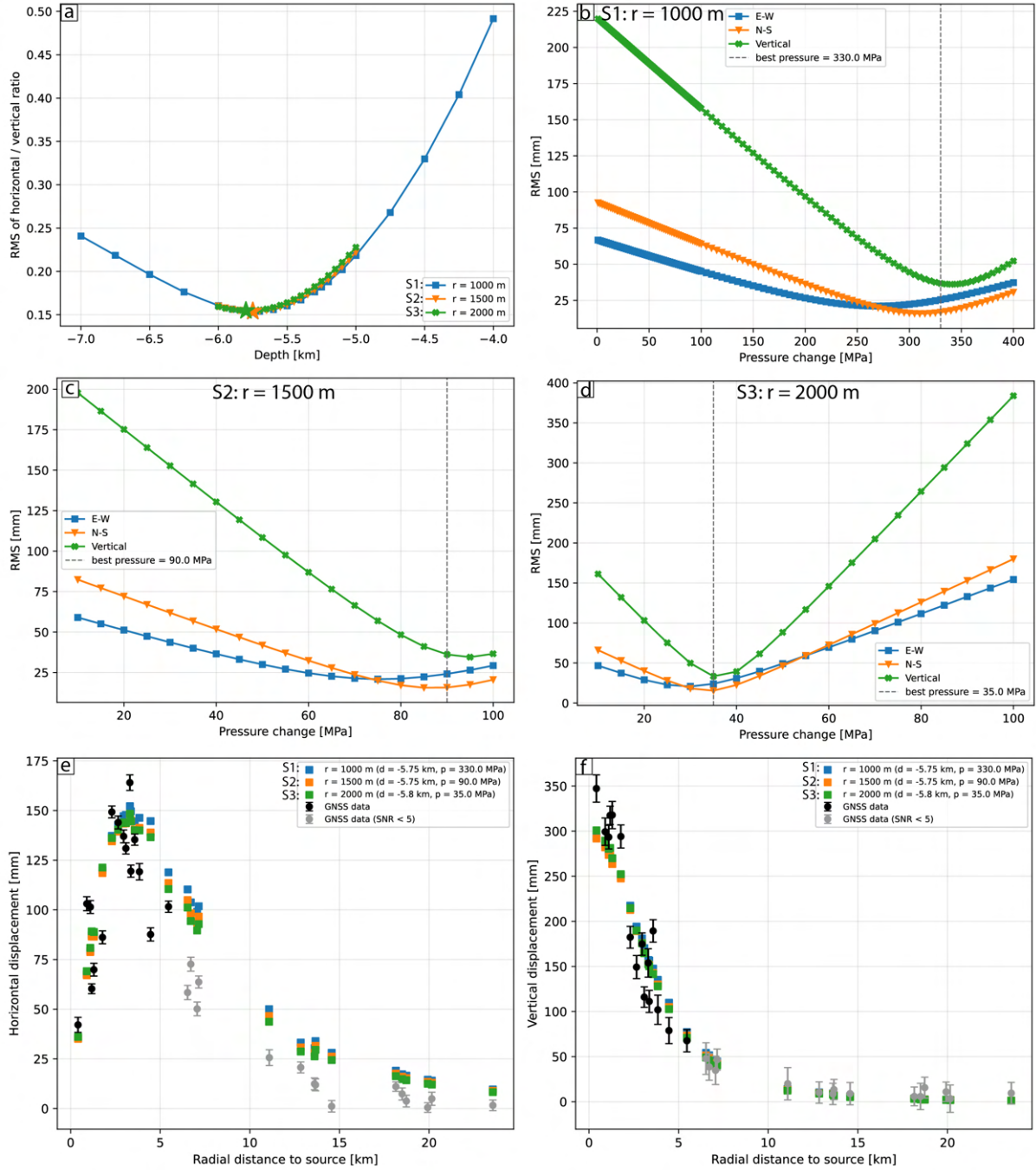


Figure 3: a) Parametric sweeps over the depth for models S1–S3 and associated changes in the RMS of the ratio of horizontal/vertical displacement. b)–d) Parametric sweeps over the pressure changes for models S1–S3 and associated changes in the RMS of individual displacement components, respectively. e) Horizontal and f) vertical displacement at individual GNSS sites ordered by radial distance from the source center. Note, that points depicted as neighboring here are not necessarily close to each other in reality. GNSS data covering the time span from 5 June – 21 August 2024 from Lanzi et al. (2026).

to increasing source volume, but it also resulted in a minor shift towards a larger depth and a slight improvement in the goodness of fit as can be seen from the RMS for each component (Table 4). The most notable improvement is in the vertical component, where the RMS of model S3 decreased by

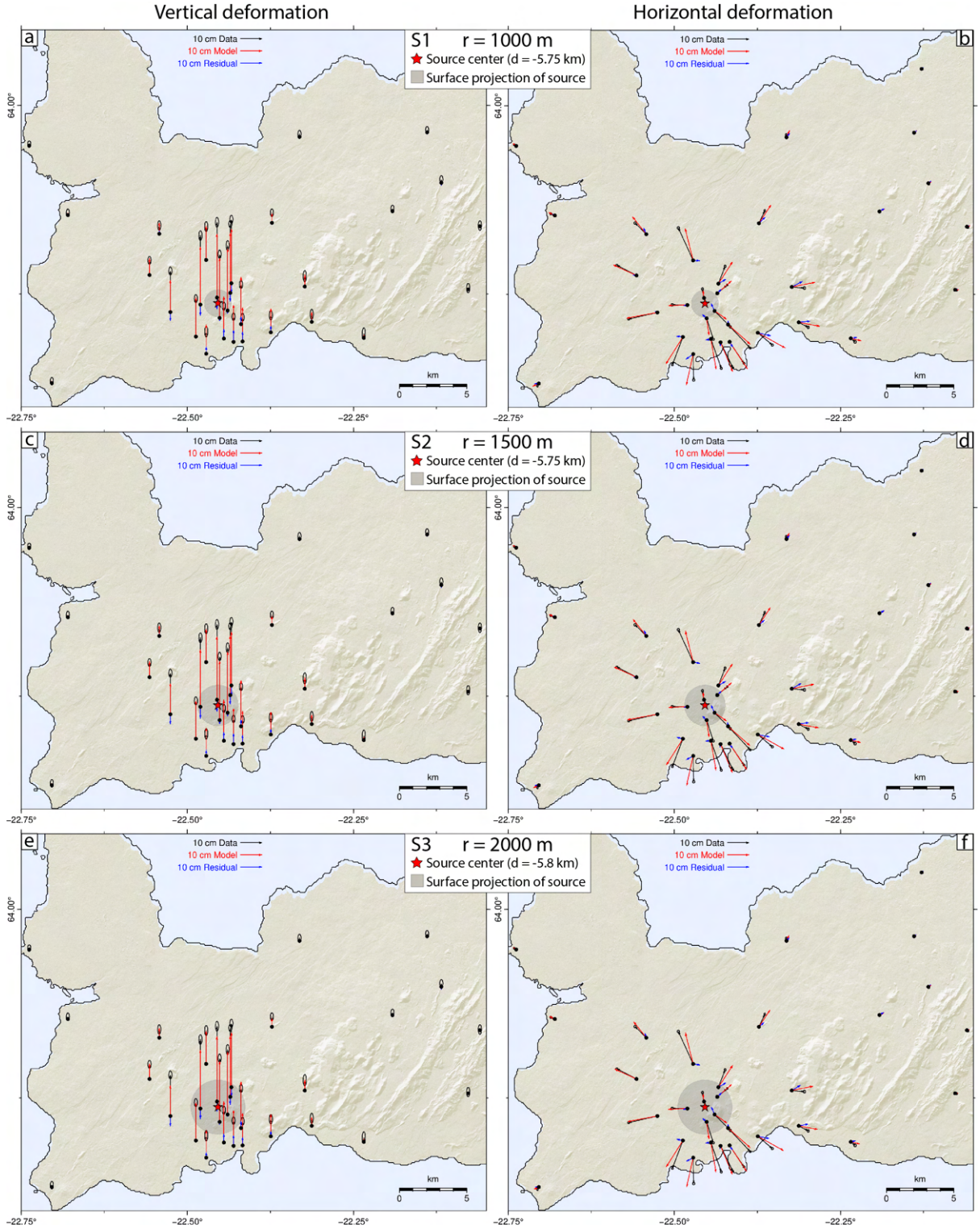


Figure 4: Comparison between modelled and observed displacements at GNSS-benchmarks for spherical source geometries. Models shown are a)–b) S1 ($r=1$ km), c)–d) S2 ($r=1.5$ km) and e)–f) S3 ($r=2$ km). a), c) and e) show vertical displacements, b), d) and f) show horizontal components. GNSS-data covers the time span from 5 June – 21 August 2024 and is from Lanzi et al. (2026).

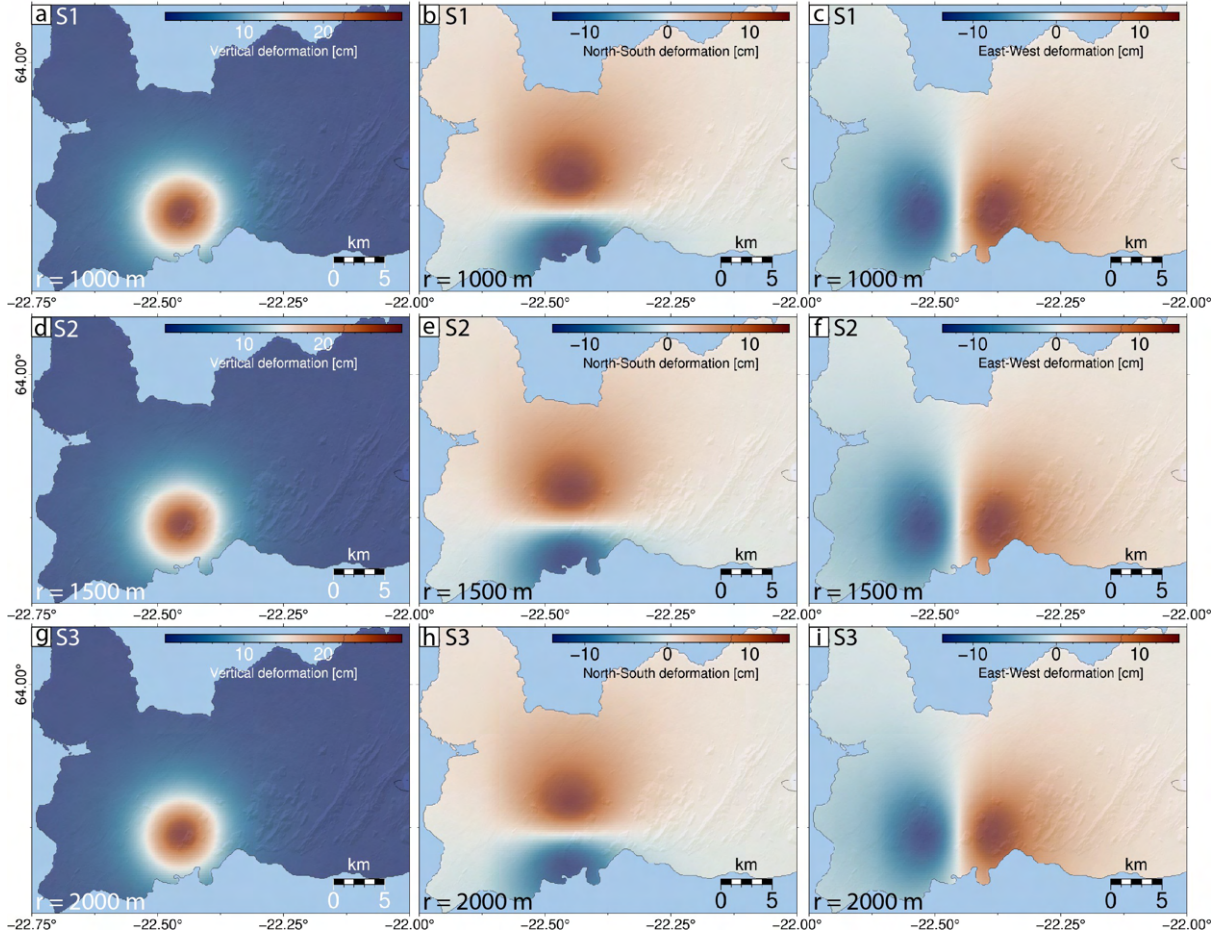


Figure 5: Surface deformation predicted by models a)–c) S1, d)–f) S2 and g)–i) S3. a), d) g) show vertical displacement, b), e) and h) show north-south displacement, and c), f) and i) show east-west displacement.

ca. 9% relative to the RMS_{vert} of model S1. The models produce symmetrical outward horizontal movement and uplift with almost identical amplitudes (Figures 4 and 5). Farther away from the source, deformation is well reproduced, although vertical deformation is somewhat overestimated southeast of the source and somewhat underestimated towards the northwest (e.g., Figure 4e). In the horizontal component, the amplitude of deformation fits better west of the source than east of it and the azimuth of the deformation differs mostly north and south of the source center (Figure 4f).

The addition of crustal heterogeneity did not cause any clearly visible asymmetry in the surface deformation (Figure 5). However, at depth the different source radii of models S1–S3 change the value of the elastic parameters directly adjacent to the reservoir boundary. This effect is likely most pronounced at the top of the reservoir, since the gradient in the elastic model is steepest along the z-axis (Figure 2a and c). At the surface this manifests in slight variations in the amplitude of deformation, which are most pronounced in the horizontal component around 3–5 km from the source center and in the vertical component directly above the source (Figure 3e, f).

6.2 Prolate Ellipsoid

Among the models using a prolate ellipsoid, the best fit to observations was achieved using a central source depth of 5.5 km, a strike (of the long axis) along N60°E and a pressure change of 25 MPa and

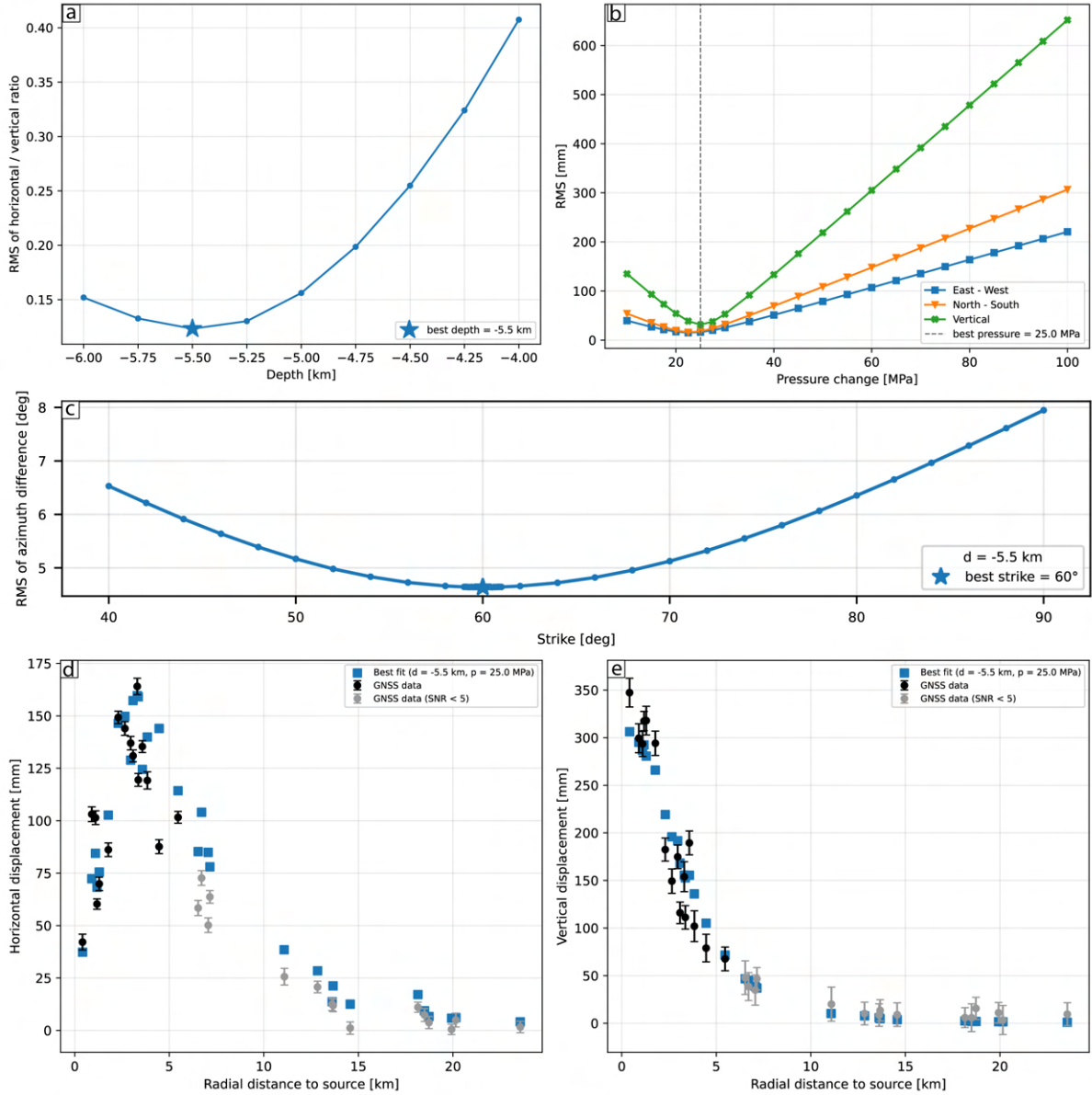


Figure 6: Parametric sweeps over a) the depth and b) the pressure change for model PE and associated changes in the RMS of the ratio of horizontal/vertical displacement and individual displacement components, respectively. c) Parametric sweep over the strike of the major semi-axis a and associated changes in the RMS. d) Horizontal and e) vertical displacement at individual GNSS sites ordered by radial distance from the source center. Note, that points depicted as neighboring here are not necessarily close to each other in reality. GNSS data covering the time span from 5 June – 21 August 2024 from Lanzi et al. (2026).

produced a volume change at the source of $21 \cdot 10^6 \text{ m}^3$ (Figure 6, Table 3). For the pressure sweep, the best-fitting model for the vertical component was shifted towards a slightly higher pressure change compared to the horizontal components (Figure 6b). Considering the source dimensions, the highest point of the reservoir is located at 4.0 km, which is directly underneath the center of inflation.

Similarly to the spherical sources, the vertical displacement is slightly underestimated for GNSS stations northwest of the center of inflation and slightly overpredicted southeast of it (Figure 7a). The

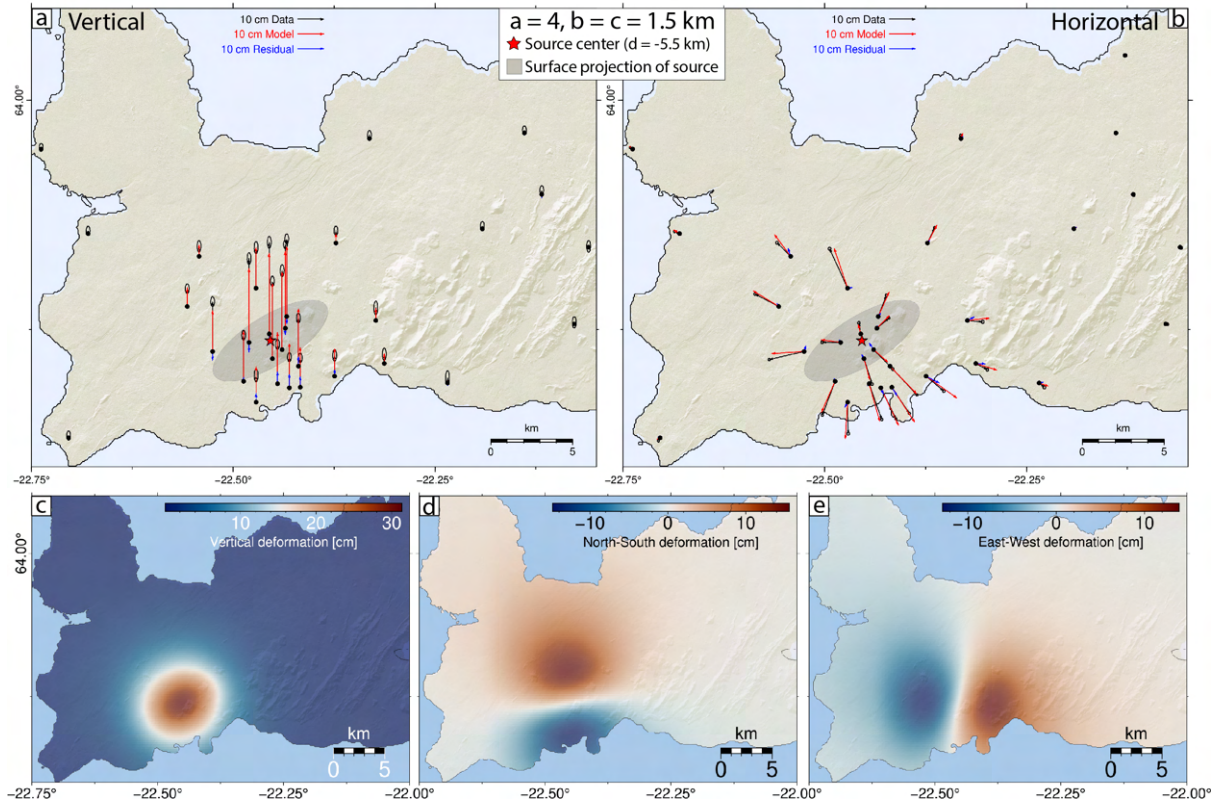


Figure 7: Comparison between observed and modelled displacement at GNSS-benchmarks for a) vertical and b) horizontal movements for model PE (prolate ellipsoid). GNSS-data covers the time span from 5 June – 21 August 2024 and is from Lanzi et al. (2026). c) Vertical, d) North-South and e) East-West components of the modelled surface deformation. See Table 2 for source dimensions.

azimuth of the horizontal displacement vectors improved overall compared to the spherical models, although especially stations east of the source fit slightly worse and stations southeast still slightly over-predict compared to observation (Figure 7b). While RMS of the eastward and the vertical component of deformation improved by 33 % and 5 % or 7.9 mm and 1.9 mm, respectively, the RMS of the northward component increased by 14 % or 2.2 mm. Presumably due to the depth of the source, the surface displacement shows a relatively mild elongation (Figure 7d), which relates to that the RMS showed only a weak dependency on variations of the strike of the source (Figure 7c).

6.3 Triaxial Ellipsoid

The best fitting triaxial ellipsoid with the dimensions $a = 4000$ m, $b = 1500$ m and $c = 500$ m is located at a central depth of 5.25 km with a N60°E strike (of the long axis), a -10° dip towards NW (the rotation axis is the long semiaxis with the southeastern edge at slightly shallower depth than the northwestern one) and a pressure change of 27.5 MPa (Table 3, Figure 8). With the central depth of 5.25 km, the shallowest point of the reservoir is located at ca. 4.8 km. The ratio of horizontal to vertical deformation is only weakly influenced by the dip with a best depth of 5.25 km for dip values between -10– +5° (Figure 8a), but strongly influenced by the depth. A two dimensional sweep over the pressure change and the dip showed the lowest RMS at -10° dip and 27.5 MPa pressure change (Figure 8c). The pressure minimum at 27.5 MPa is for dip values between -15° and -5°, indicating that it is relatively robust. The vertical displacement component is more sensitive to pressure changes than the horizontal

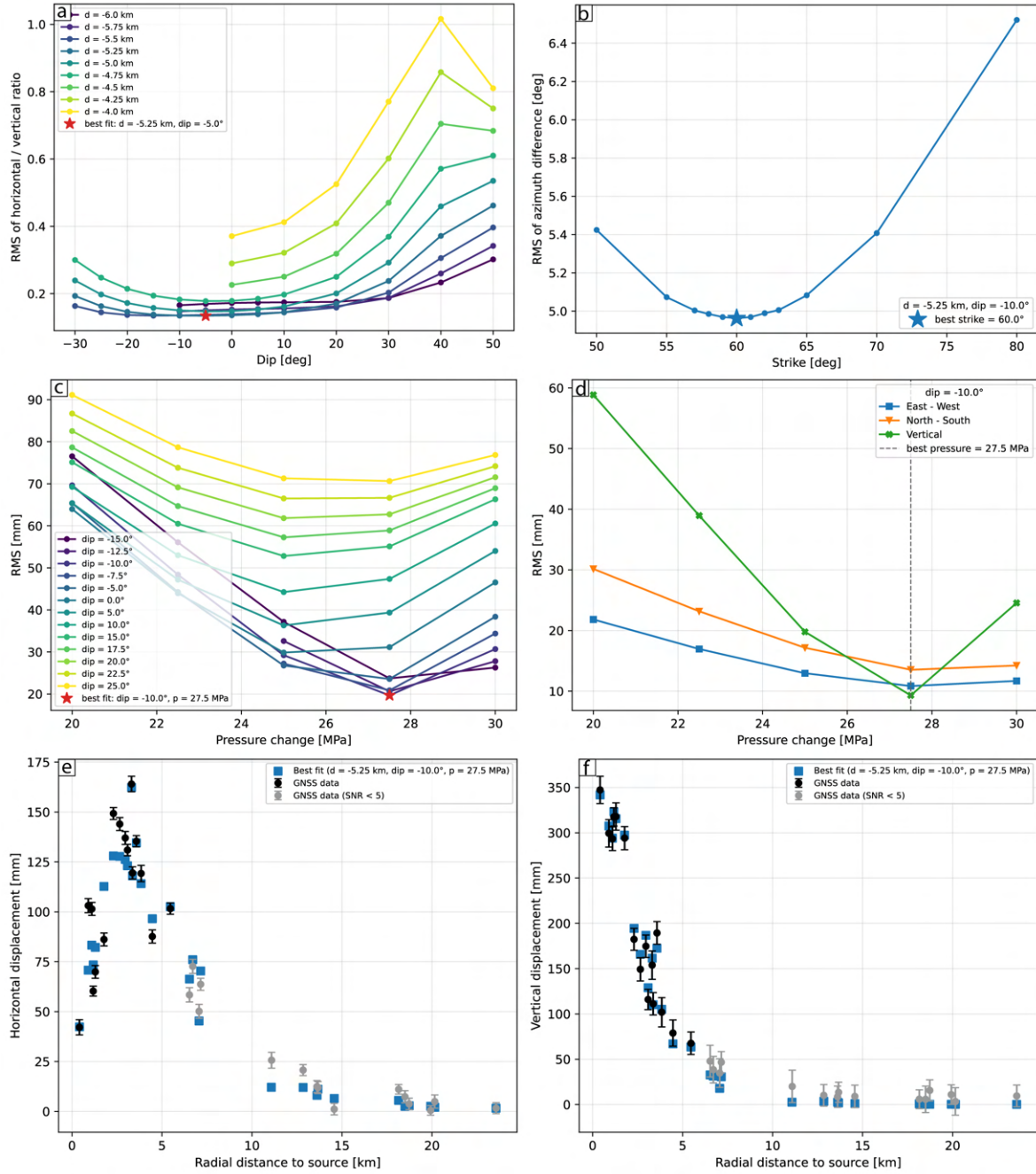


Figure 8: *a) Two-dimensional parametric sweep for model TE over the depth and the dip (around the major reservoir semi-axis a) and associated changes in the RMS of the ratio of horizontal/vertical displacement. b) Parametric sweep over the strike and associated changes in the RMS of individual displacement components. c) Two-dimensional parametric sweep over the pressure and the dip (around the major reservoir semi-axis a). The y-axis shows the combined RMS of all three displacement components. d) Component-wise RMS for the best-fitting dip of -10° as a function of the pressure change. e) Horizontal and f) vertical displacement at individual GNSS sites ordered by radial distance from the source center. Note, that points depicted as neighboring here are not necessarily close to each other in reality. GNSS data covering the time span from 5 June – 21 August 2024 from Lanzi et al. (2026).*

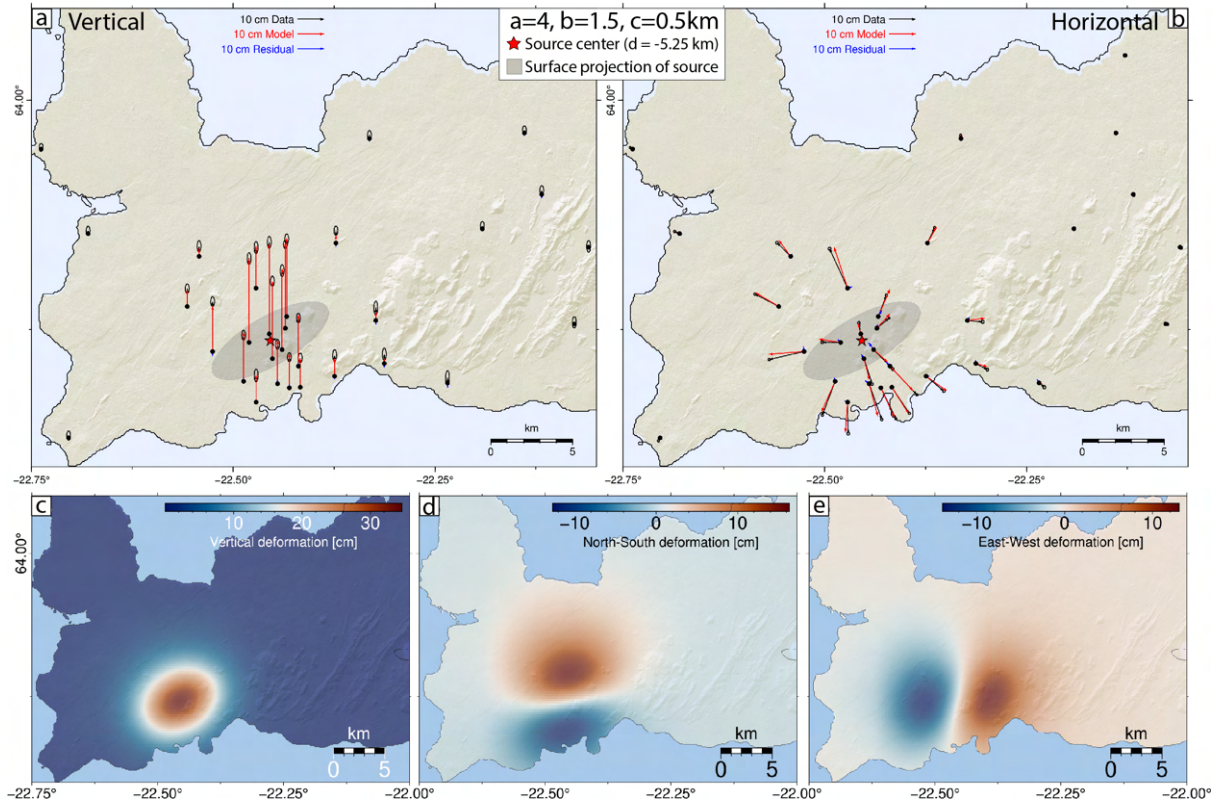


Figure 9: Comparison between observed and modelled displacement at GNSS-benchmarks for a) vertical and b) horizontal movements for model TE (triaxial ellipsoid). GNSS-data covers the time span from 5 June – 21 August 2024 and is from Lanzi et al. (2026). c) Vertical, d) North-South and e) East-West components of the modelled surface deformation. See Table 2 for source dimensions.

components (Figure 8d).

The RMS for the TE model show improved fits for all three components with the most drastic improvement in the vertical component, where the RMS for model TE is just ca. 30% of the RMS for the PE model and 28% of the RMS for the best-fitting sphere, corresponding to an improvement of 70% and 72%, respectively (Table 4). In the horizontal components, improvements are somewhat smaller but still notable ranging from 13-55% (Table 4). The model TE captures the vertical displacement especially well with almost all predicted displacements within uncertainty limits of the GNSS-observations (Figure 8f, Figure 9a). The overestimation of horizontal motion southeast of the inflation center and simultaneous underestimation of displacement to the northwest, which was observed for previous models, is largely removed (Figure 9b). Instead, there is a slight overcorrection in the southeast, resulting in underestimation of deformation compared to the GNSS-data. As for previous models, the overall surface deformation still shows a high degree of symmetry (Figure 9c-e), although the vertical deformation is the most visibly elongated along the NE-SW axis out of all models presented here.

7 Discussion

Among all model geometries tested here, the triaxial ellipsoid (model TE) produced the best fit to the GNSS data (Table 4). The vertical component showed excellent agreement, especially considering that the model parameters were modified manually rather than in an inversion. Differences in the best-fitting pressure change estimates between deformation components within individual models were largest for

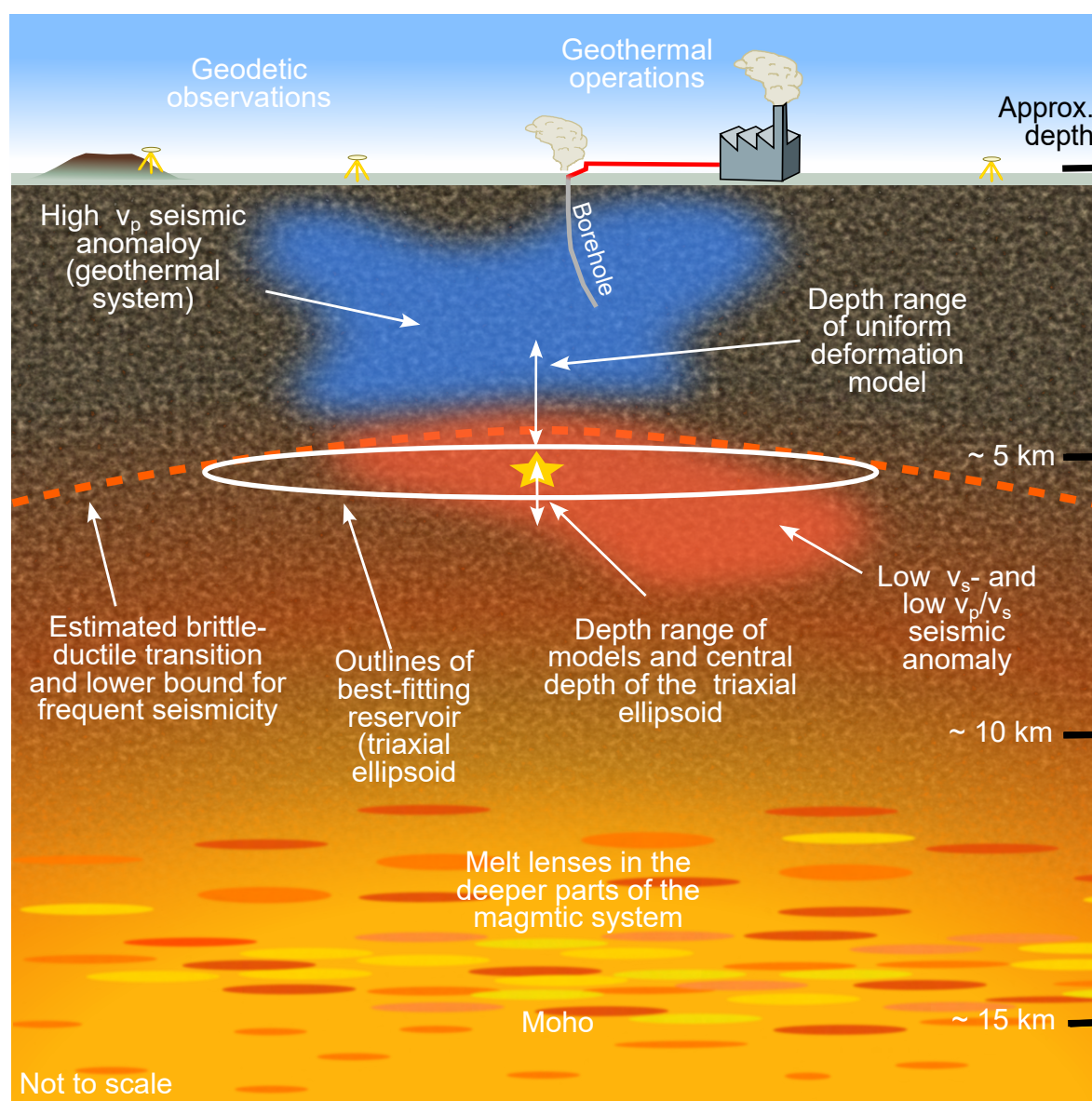


Figure 10: *Conceptual model of the magmatic system and crustal structure underneath Svartsengi. The outlines of the seismic velocity anomalies are qualitatively based on the work of Allas et al. (2026). Note that the figure is not to scale.*

the spherical sources, especially between the vertical and eastward components of motion, which can be taken as an indication that the source geometry is not a good representation of the actual source (Figure 3b-d). In contrast to this, model TE, which has the overall best fit, also suggests consistent best-fitting pressure estimates between individual components of motion (Figure 8d). This consistency can be taken as an additional indicator that a vertically flattened triaxial ellipsoid is a better approximation for the deformation source than a spherical source.

The spherical sources required the largest central depths out of the geometries tested here with up to 5.8 km. However, with only 600 m, the overall range of the central depth is relatively narrow. Similarly, the depths of the highest points of each reservoir are located between 4.75–3.75 km with shallower top depths and less curved roofs obtaining better fits. Deeper source estimates for spherical or point

sources compared to ellipsoidal source geometries are common for deformation models (e.g., Greiner and Geirsson, 2024; Lanzi et al., 2026).

The pressure changes in the model vary significantly and are tied mainly to the volume of the source, as is demonstrated by the spherical models S1–S3. The three best-fitting models produce pressure changes in the range of 25–35 MPa, which, although on the higher end, are comparable to estimates for failure conditions (Schultz, 1995; Currenti and Williams, 2014). Presumably due to the relatively large source depth, the strike and dip were secondary controls for the RMS compared to the depth and the pressure change (e.g., Figure 8a,c).

It is common for models considering crustal heterogeneity to obtain larger source depths than uniform models (Masterlark, 2007; Hickey et al., 2015; Greiner and Geirsson, 2024; O’Hara, 2023). This trend is confirmed with models presented here being 1.5 km (prolate ellipsoid) and 1.9 km (spheres) deeper than models with an equivalent geometry and uniform elastic host rock (Sigmundsson et al., 2024; Parks et al., 2025; Lanzi et al., 2026). The depth-estimates found in the present study align very well with the 5.4 ± 4.7 km depth estimate derived from thermobarometry using Cpx-liquid equilibration pressures for crystal cores of enriched melts Matthews et al. (2024). However, their analysis is based on products from the first eruptions, during which geodetic inversions by Lanzi et al. (2026) also found larger source depths compared to the later episodes. Overall, the source depths are consistent with previous findings, but suggest a slight shift to larger depths of 5.25–5.8 km.

If using the parameters for a spherical point source suggested by Lanzi et al. (2026) for the time span of 5 June–21 August 2024 and comparing to the GNSS data, the RMS values for the different components of motion are $RMS_{EW,ana} = 20.7$ mm, $RMS_{NS,ana} = 17.0$ mm and $RMS_{vert,ana} = 30.0$ mm. Compared to this, the RMS values of model TE ranging between 9–14 mm are an improvement, especially in the vertical component (Table 4). However, the RMS values of analytical models are comparable and in some cases even lower than those of the spherical models S1–S3, which is a reminder for the general non-uniqueness of geodetic models. Furthermore, the volume changes found in the present study and those found by Lanzi et al. (2026) ranging from 15–25 million m³ are comparable, which is consistent with that the ratio of intruded vs. uplifted volume depends mainly on the source geometry (Delaney and McTigue, 1994). This indicates that geodetically derived volume estimates are not, or not significantly, affected by considerations of elastic crustal heterogeneity.

The triaxial ellipsoid in model TE is of special interest, because there is no direct equivalent analytical model to compare it to and numerical models can provide new insights here. The Okada-sill inverted for by Parks et al. (2025) and Lanzi et al. (2026) is significantly narrower (600 m wide) than the total width of the triaxial ellipsoid in our model, which was fixed a-priori based on estimates from Sigmundsson et al. (2024) and not varied. While the strike is similar between the Okada-sill and the TE, the dip is less than 1° in the inversions by Parks et al. (2025). The flattened, but still non-planar shape of model TE opens the question of what the source reflected in the surface deformation corresponds to. If the TE, or at least its upper half, is an accurate resolution of the source, it could reflect the top of the magmatic reservoir rather than for example the point at which magma flows into the reservoir. Alternatively, it could reflect an individual sill within the larger reservoir, which is surrounded by and exerts pressure onto a significant volume of ductile material, in case of which the TE-surface would correspond to the outer limit of the ductile material. However, the volume of the triaxial ellipsoid appears to be too small to correspond to the entire magma reservoir, so we suggest that the first option, i.e. that the TE reflects the roof of the reservoir, appears more likely (Figure 10).

Although no FEM-inversions were implemented here, observations could be reproduced with only minor residuals. This indicates that heterogeneous FEM-models can be a useful addition to refine results from conventional inversions of geodetic data without requiring inversions of their own. Inversions of analogue experiments by Poppe et al. (2024) showed that geodetic models capture the lateral location and strike of deformation sources, which in their case were sheet intrusions reasonably well. Especially if

the dimensions of the source can be estimated with external information, the depth, pressure change, and dip of magmatic sources can be constrained well with parametric sweeps by decoupling the individual source parameters.

While the present set of models may provide insights into the location and possible shape of the deformation source, additional work is required for further constraints. These models should include a more realistic version of the source itself, which in the present study is represented simply through a uniformly pressurized cavity. Further work should also use satellite interferograms as an additional dataset to compare the FEM models with and conduct more thorough testing on the influence of the source dimensions on the surface deformation at Svartsengi.

8 Conclusions

We implemented three-dimensional elastic Finite Element deformation models of the Svartsengi volcanic system that consider crustal heterogeneity based on seismic velocity models by Allas et al. (2026) and a density model by Sigmundsson et al. (2020b) and compared them to GNSS observations from June-August 2024 (Lanzi et al., 2026). The models explored three different source geometries: spheres of three different radii, a prolate ellipsoid and a triaxial ellipsoid, which had the shortest axis aligned close to vertical.

All models could reproduce observed deformation with the best fit being achieved for the triaxial ellipsoid located at 5.25 km depth as the deformation source. All tested sources shifted the central source depths by 1.5–1.9 km compared to estimates from equivalent uniform elastic models where available, which demonstrates the importance of considering crustal heterogeneity in deformation models. Despite the larger depths, volume changes at the deformation source agreed well with estimates from previous studies. We suggest that the triaxial ellipsoid reflects the top of the magmatic reservoir at Svartsengi.

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