CONSTRAINING MAGMA CHAMBER AND RECHARGE CONDITIONS FROM SURFACE UPLIFT AT THREE SISTERS VOLCANIC CENTER IN THE OREGON CASCADES

by

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An episode of ongoing uplift in the Three Sisters volcanic center in the Oregon Cascades was discovered in 2001 from InSAR observations. The center of uplift is ~6 km west of the summit of South Sister, and the spatial pattern is consistent with a spheroidal source of inflation. The combination of InSAR and continuous GPS data since 2001 indicate a gradual onset of uplift beginning around 1996, reaching a peak of ~3-4 cm/yr between ~1998- 2004, and declining since then to a current rate of ~0.5 cm/yr (Riddick and Schmidt, 2011) . This pattern of initially rapid uplift followed by an exponential decay has been observed at several other volcanoes, such as Yellowstone, Long Valley, and Laguna del Maule (Le Mével et al., 2015), but it is unclear whether the pattern of uplift is due to magma recharge that varies with time and/or viscoelastic effects. I present a model for surface deformation due to a spherical magma chamber in a viscoelastic crust subject to recharge, cooling, crystallization, and volatile exsolution, and combine this model with InSAR and GPS data to test the recharge rates and magma chamber conditions that can best explain the variation in the uplift rates at Three Sisters. I found a spherical magma chamber at 6 km depth, a volume of 38 km^3 , and 4 wt. %

water content. I also tested for a pulse-like recharge as a cause of the uplift. The best fit solution was the emplacement of 1×10^{12} kg of magma into the chamber, estimated to last for ~15 years with a maximum recharge rate of ~4,000 kg/s occurring ~7 years after the beginning of the recharge event.

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Introduction

Around 800 million people live within 100 km of a volcano that could erupt, well within the boundaries of dangerous volcanic hazards (Brown, 2018). But understanding the underlying causes behind a volcano's behavior remains difficult and quite complicated (Brown, 2018). One aspect of volcanic behavior that is easily monitored is surface deformation at and around a volcano because it occurs at the surface of the Earth. Surface deformation is a very common signal at volcanoes even between eruptive periods. These changes are typically ascribed to magma injection or magma recharge to a magma chamber, so patterns of surface uplift at a volcano reveal aspects about the underlying magma chamber, such as depth, general geometry, and volumetric change. The information that can be gained about a magma chamber from analyzing the surface deformation can help us predict the scale and timing of eruptions that the volcano could produce. Hazard assessment at a volcano ideally would include an estimate of the volume of potentially eruptible magma, as well as an estimate of what pressure the magma is stored at and how close it is to reaching a "critical" pressure, which would then cause an eruption. Unfortunately, we can't get these estimates from classic surface deformation models. With the model I am using, which takes into consideration the effects of time-dependent recharge, cooling, crystallization, and volatile exsolution on surface deformation, I am able to place constraints on those key parameters. Using an ongoing uplift event at the Three Sisters volcanic center in the Oregon Cascades, this project aims to 1) better constrain the magma chamber under South Sister, which is located within the Three Sisters volcanic center, and 2) elucidate what changes in the magma chamber occurred to create the signal of uplift.

South Sister was largely ignored as a volcanic hazard until surface uplift was recorded by satellites in the late 1990's. But this uplift even went unnoticed by scientists until 2002 when it was discovered by Wicks et al. (2002). This event prompted the United States Geological Survey (USGS) to set up multiple GPS stations and run several GPS campaigns throughout the 2000's and 2010's to monitor this uplift event. The combination of Interferometric Synthetic Aperture Radar (InSAR) and continuous GPS data indicate the center of uplift to be ~6 km west of the summit of South Sister and had a gradual onset of uplift beginning around 1996, reaching a peak rate of ~3-4 cm/yr between ~1998-2004, and declining since then to the current rate of ~0.5 cm/yr (Riddick and Schmidt, 2011). This surface deformation pattern of initially rapid uplift followed by exponential decay is a common behavior amongst volcanoes and has been observed at several other volcanoes, such as Yellowstone, Long Valley, and Laguna del Maule (Le Mével et al., 2015).

Estimation of magma chambers using surface deformation data is traditionally constrained to only the depth, volume change, and geometry of the chamber. Estimates on the cause of uplift in the first place or causes of the exponential decay, which was observed at South Sister and elsewhere, are not found in traditional surface deformation models. There is some discussion around integrating models for physical processes occurring within a magma chamber to surface deformation. Townsend (in review) discusses the use of different solutions for linking magma chambers to surface deformation, it also presents the model that I will be using for this project.

To constrain the magma chamber under South Sister and the various conditions that could have created the signal of uplift observed, I used a model for a spherical magma chamber in a viscoelastic half-space subject to recharge, cooling, crystallization, and volatile exsolution linked to surface deformation. Then by combining this model with InSAR and GPS data taken from South Sister, I am able to place constraints on the volume, depth, and location of the magma chamber under South Sister as well as the magma injection conditions to the chamber that caused it to inflate.

Geologic Background

The Three Sisters Volcanic Center and South Sister

South Sister is one of three geologically distinct stratovolcanoes within the Three Sisters volcanic center; the other two are North and Middle Sister. They are located in the Central Oregon Cascades. The volcanoes of the Cascade Arc are stratovolcanoes that were formed, and are fed, by subduction zone magmas. In the case of the Cascades, the subducting Juan de Fuca plate under the North American plate is the cause of the volcanism.

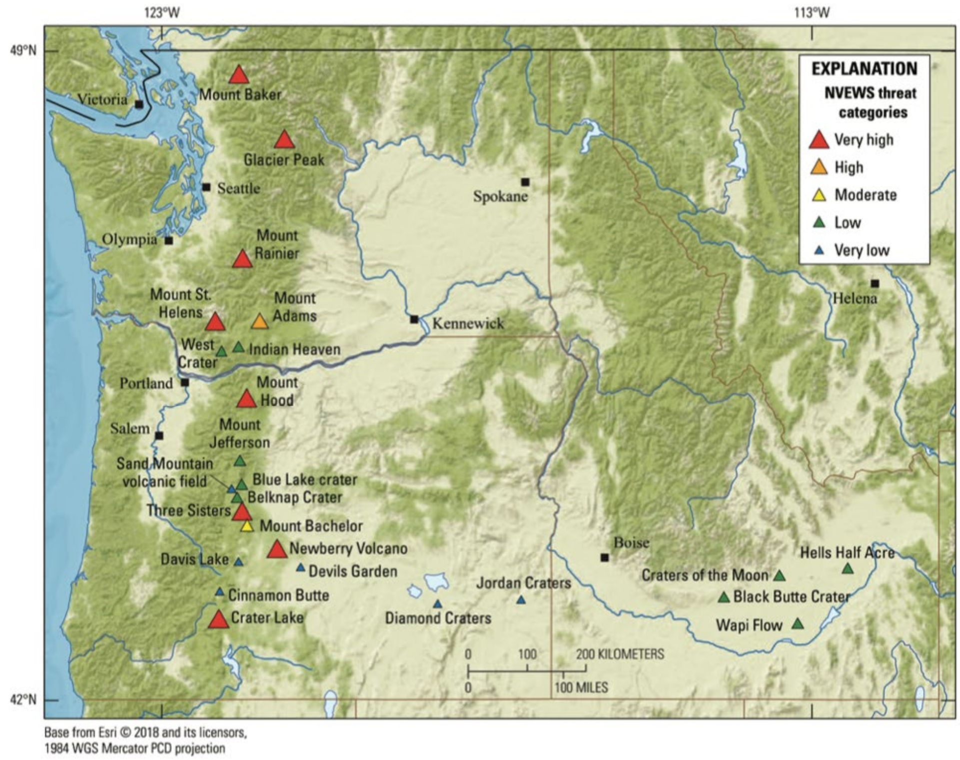

Figure 1: Location map of the Three Sisters within the Cascades

From the National Volcano Early Warning System (NVEWS) of Oregon and Washington State (from Ewert et al., 2018). Warmer colors represent a higher volcanic thereat.

The three main stratovolcanoes in the Three Sisters complex were formed at different times with differing geology. North Sister is the oldest of the three with estimates placing its oldest formations at ~120 thousand years ago (kya) and the youngest formations at ~50 kya. North Sister is mainly mafic in composition (Fierstein et al., 2011). Middle Sister is the shortest of the Sisters but is considered to be contemporary with South Sister. Middle Sister is considered to be between ~48 kya and ~14 kya and is composed of andesite, basalt, and dacite (Fierstein et al., 2011). South Sister is the highest and most recently geologically active with its formation occurring between ~50 kya to ~2 kya. South Sister's composition alternates throughout its formation with rhyolitic and intermediate units (Fierstein et al., 2011). The most recent eruptions at South Sister (~2 kya) occurred at the southwest flank (Rock Mesa) and at a dike-fed chain of flows trending north/south (Devils Chain) on the southeast flank of the volcano (Fierstein et al., 2011).

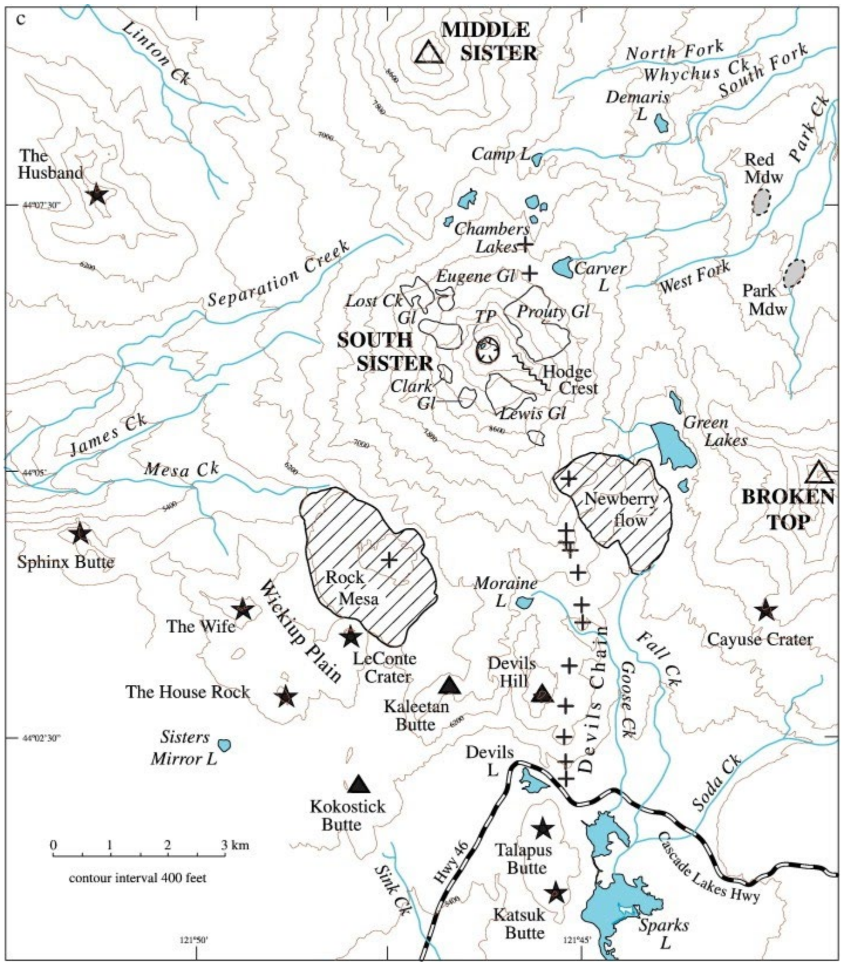

Figure 2: Location map of South Sister region

It is a location map on and around South Sister. Lake (L); Glacier (Gl); Teardrop Pool (TP); mafic peripheral vents (stars); large composite centers (open triangles); silicic domes (filled triangles); Holocene rhyolite vents of Devils Chain (pluses) (from Fierstein et al., 2011).

Pre-existing Literature

This project is made possible by the identification of surface deformation at South Sister as published by Wicks et al. (2002). Despite the onset of inflation occurring around 1995, it remained undiscovered for ~6 years when Wicks et al. discovered it by looking through historical InSAR data. As this was only ~20 years after the 1980 St. Helens eruption there was an interest in predicting the Cascades volcanoes' eruptions, and South Sister became a concern. In 2001, the USGS placed the first of 2 permanent GPS stations around South Sister to monitor the deformation.

The next paper to address the uplift at South Sister is by Dzurisin et al. (2006). This paper begins to address the possible geometry of the source of inflation under South Sister. This paper draws upon the use of InSAR, GPS, and tilt-leveling measurements to estimate the size, shape, and volume increase of the magma chamber. A reliance on InSAR data for early measurements skewed the modeling of the magma chamber to best be fit by a dipping sill (Dzurisin et al., 2006). And after another leveling and GPS campaign, Dzurisin et al. published another paper on South Sister in 2009. This 2009 paper was published after the rate of inflation at South Sister had exponentially decayed, and the threat of South Sister erupting was reduced. And by this point many more GPS stations had been utilized as part of a short campaign and the reliance on InSAR data fell. This led to the conclusion that the previous paper in 200 wrongly assumed the shape of the magma chamber to be a sill when it was much more likely to be a spherical point source (Dzurisin et al., 2009).

Riddick and Schmidt (2011) further characterized the rates of surface uplift by creating the first time series. This paper relied entirely on InSAR observations and magma chamber modeling. It is the first paper to link the decay of surface uplift at South Sister to a swarm of small magnitude earthquakes in the northeast corner of the uplifting region. It is also the first paper to suggest a gradual onset of surface uplift at ~1 cm/yr in 1996 followed by the more rapid ~3-4 cm/yr rates from 1998-2004 .

The most recent paper discussing the uplift event was published by Rodríguez-Molina et al. (2021), who estimated the size and location of the magma chamber causing this event using a combination of InSAR and GPS. They created a continuous LOS time series from the onset in 1996 to 2020, as well as processing the data collected at one of the continuous GPS stations monitoring this event. They come to the conclusion the best fitting geometry of the magma chamber is a spherical point source between 4.5-6 km depth and with a ΔV $(7-13) \times 10^6\ m^3$. They also theorize that the decay of the rate of uplift is due to the viscoelastic response of the crust around the magma chamber (Rodríguez-Molina et al., 2021).

Research Questions

In this project I hope to address several questions. The first is to add to the history of efforts to determine the depth, location, and size of South Sister's magma chamber. However, to determine these kinematic aspects I will be using a model that also incorporates physical processes as well. These non-kinematic elements of the model may provide further insight into the chamber conditions (size and pressure). The second question I am considering by using these more advanced models is the cause of this deformation signal in both its cumulative uplift and its rate of uplift. I will take into account the effects of magma recharge, viscoelastic relaxation of the crust, and the interplay of both to help determine the causes of uplift at South Sister.

Methods

In order to determine both kinematic aspects and physical processes within the magma chamber under South Sister, these three tasks had to be completed: 1) collect and prepare surface deformation data over the South Sister region, 2) choose a model for magma chamber evolution linked to surface deformation and tailor it to the South Sister system, and 3) run a Markov-Chain Monte Carlo (MCMC) algorithm to identify combinations of magma chamber and recharge parameters that best fit the surface deformation data.

Data Collection

InSAR

Interferometric Synthetic Aperture Radar (InSAR) was chosen as one of the main sources of data to be used in the modeling process because it spans the entirety of the uplift event and provides good spatial resolution compared to other methods like GPS. InSAR is a satellite-based measurement of ground deformation recorded by repeated flights over a region. An electromagnetic wave with a known wavelength is aimed towards the surface of the Earth, then reflects against the surface, and the phase shift of the wave is recorded by the satellite. When two of these observed phase shifts are compared to each other, an interferogram is produced which shows the interference of the waves and their shifts, either constructively or destructively ("InSAR—Satellite-based technique").

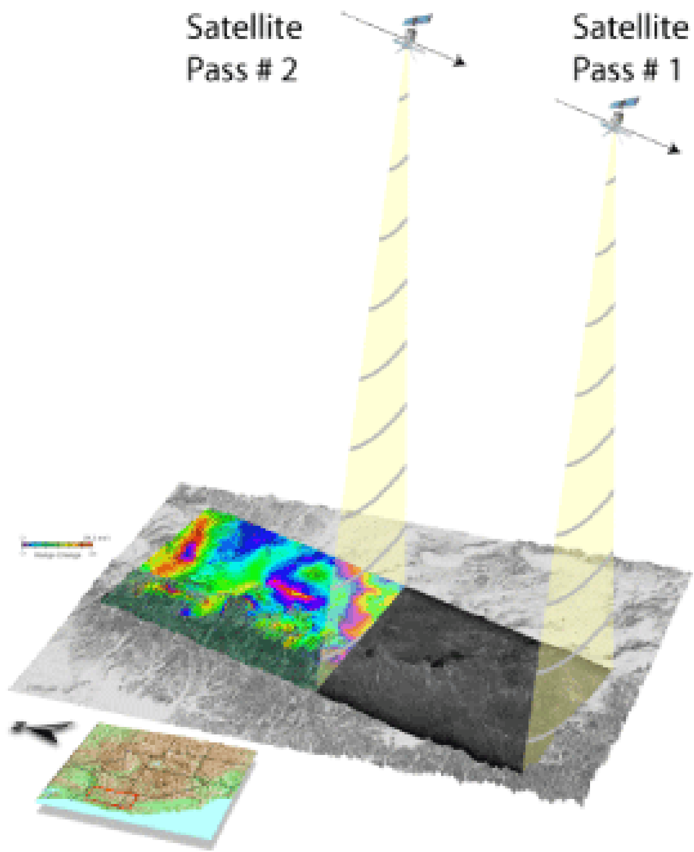

Figure 3: Conceptual figure of InSAR

It shows the repeated flights over a region and the products created by each flight (Public domain via USGS).

For this project, I created an InSAR time series from the beginning of the deformation event until present day. A time series is the comparison of several interferograms and results in a plot of line-of-sight displacement (LOS) vs. time. Uplift began around 1996, so the time series is from 1995-2020. Since this is a relatively long time period compared to the operational lifespan of a satellite, no singular satellite observed the deformation event. Five satellites had to be used: the first satellites used in the time series are ERS-1 and ERS-2 from 1995-2001, the second satellite is Envisat from 2003-2010, and the final satellites used are Sentinel-1A and 1B from 2015-2020 (also referred to as just Sentinel-1), all satellites have been launched by the European

Space Agency (ESA) . Also, due to low coherence in the interferograms due to snow coverage, only summer (June-October) images were used to make the interferograms. The region of uplift is situated within the Three Sisters Wilderness area, so the dense vegetation from the protected land generally leads to a lower baseline coherence. Then in the Cascades, the snow cover for most of the year decreases the coherence during the winter and early spring, so summer images are used to maximize coherence. Also in the interest of minimizing errors in LOS displacement the mountains themselves were cropped out of some of the processed interferograms. The formation of gravity waves as masses of air move up the side of the mountain may create false signals of displacement in the InSAR data.

To create the LOS time series, the same general process was used for all three satellites. First, the unprocessed images were downloaded from a database and paired to another image to create interferograms. With n representing the reference image, these pair combinations typically would include the adjacent image in time (n + 1) and the next adjacent image (n + 2), but in some cases, all pairing combinations were processed in order to handle low coherence of the interferograms, or a small number of images in general. Figure 4 shows an example of these pair combinations for the ERS 1 & 2 satellites. Once the interferograms were created, they were then processed again to create the time series for that satellite. For the ERS-1, ERS-2, and Envisat time series, all the individual interferograms had to be checked by hand for coherence and incoherent interferograms were discarded.

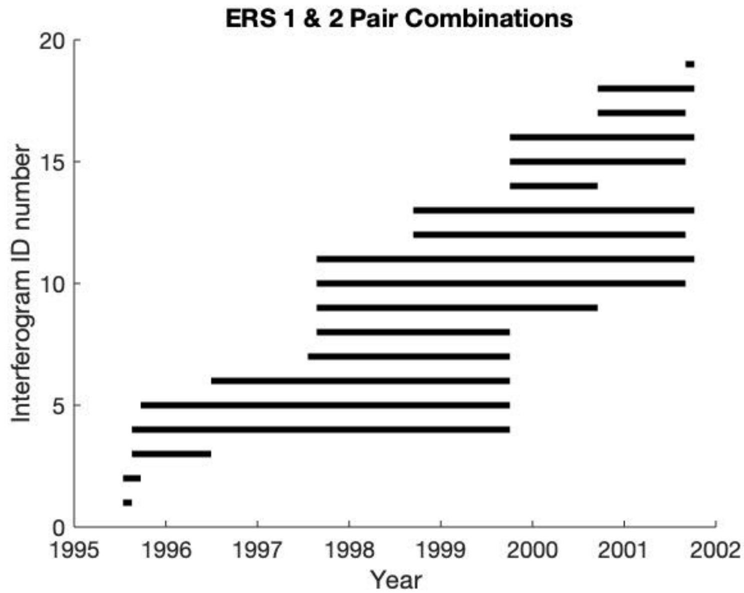

Figure 4: Plotted pair combinations for the ERS-1 and ERS-2 satellites

The left side of each black bar is the date of the primary image while the right side is the date of the secondary image. The length of the black bar represents the amount of time between the primary and secondary images.

GPS

The GPS stations have been used to monitor this uplift event since its identification in 2001. The USGS has placed several permanent stations starting in 2001, and in recent years semi-permanent stations have been used during the summer season. These semi-permanent stations have not been used in prior estimations of South Sister's magma chamber. The GPS stations provide a high temporal resolution and help to bridge the gaps left between satellites in the InSAR data. In order to make the GPS data compatible with the model outputs I had to calculate cumulative uplift/vertical displacement and cumulative radial displacement

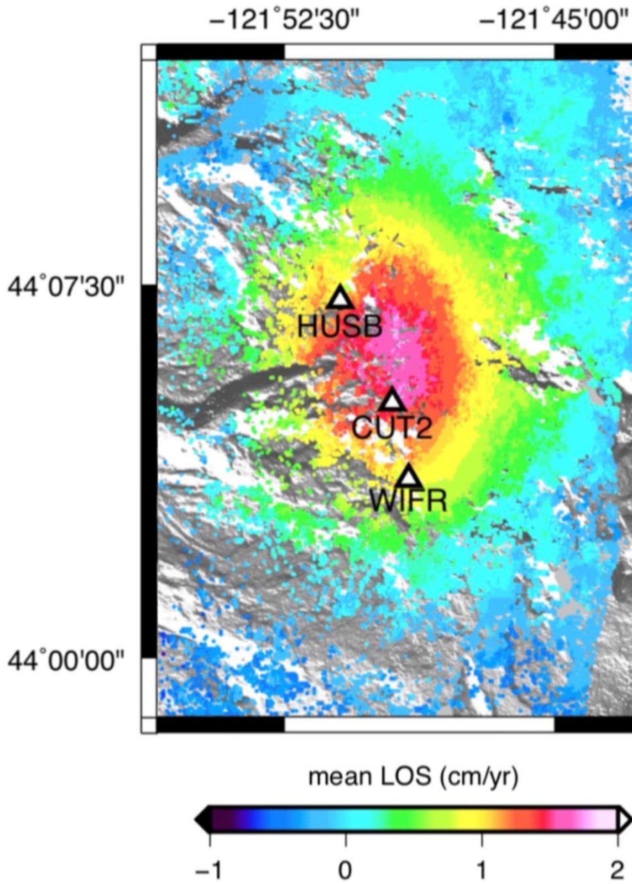

Figure 5: Locations of the GPS stations

Shows the location of the GPS stations in relation to the signal of uplift from the ERS-1 & 2 satellites (1995-2001).

I calculated cumulative vertical displacement and cumulative radial displacement for each GPS station in the region. In order to do this, I first processed all the downloaded GPS data from the USGS website, specifically from the Sisters Network website, into a Matlab-usable form. I then removed the movement of the North American plate by comparing the stations experiencing uplift to a GPS station that was in the region but not experiencing uplift from South Sister. The selected control station is coded as P385 and is north of the region of uplift. By subtracting P385 from the uplifting stations I was able to remove the movement of the North American plate. Then to calculate the cumulative vertical displacement I subtracted each station's first value from each value since.

Calculating cumulative radial displacement was trickier. I had to determine the coordinates of the center of uplift for this event and calculate the distance of each station from that point. I then used trigonometry to estimate the cumulative radial displacement from the east/west and north/south values recorded by the station. This step made some assumptions, first that each data point was taken with respect to the station's original position when it was placed. And the second is that the radial displacement is additive so that the last data point in the set is the cumulative displacement of all the previous data points.

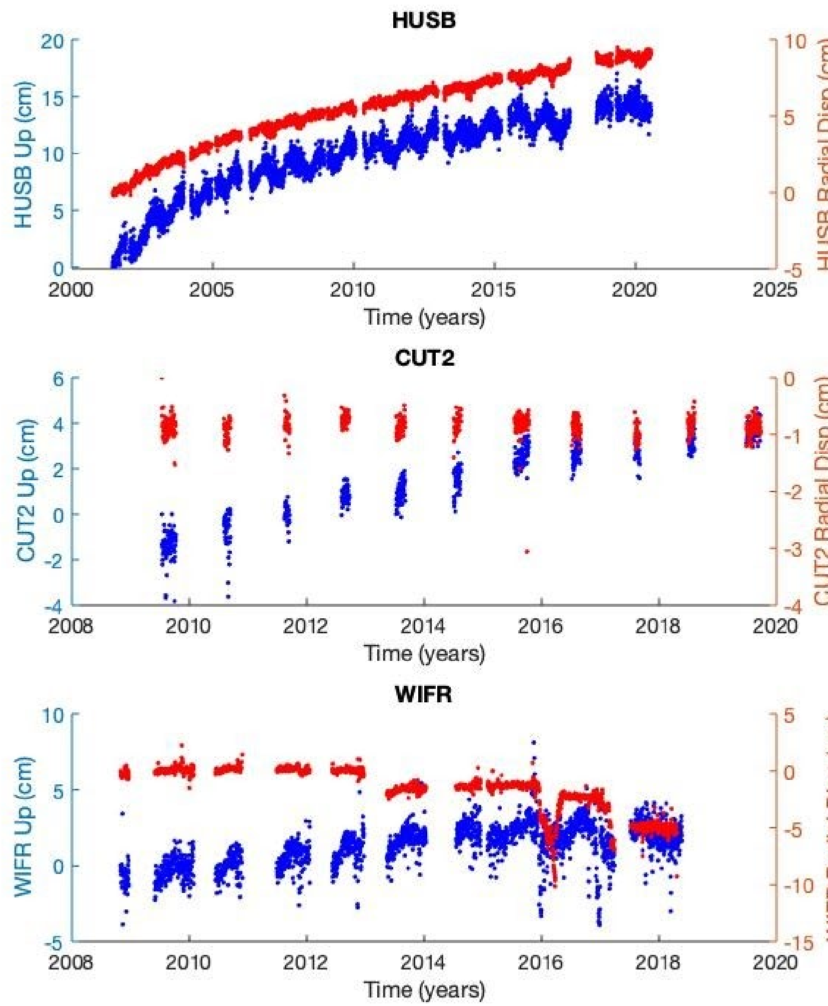

Figure 6: GPS time series

The cumulative vertical displacement (blue) and the cumulative radial displacement (red) of each GPS station over time.

For this project, GPS was used as an independent check on the accuracy of the InSAR data. It also helped to compare the general shape of the model's output of cumulative displacement vs. time, since the HUSB station has been continuously monitoring the event since 2001. The location of the GPS stations relative to the surface deformation event is shown in figure 5, while the cumulative and radial displacement of each station is shown in figure 6. In the future I hope to add the GPS data into the considerations that the model takes into account when estimating the likelihood of a set of chamber parameters.

The Magma Chamber Model

The model used for this project is a model of magma chamber recharge and is different from previous models used to estimate South Sister's magma chamber. This model predicts the kinematic aspects of the model, which has been done previously, and some physical properties of the magma chamber. Based on the spatial patterns of deformation at South Sister, and given that this is a volcanically active region I hypothesize that deformation is due to the injection of magma into a magma chamber located beneath the deforming area. Magma recharge/injection would pressurize the magma chamber, leading to an increase in volume that pushes on the surrounding rock and causes the earth's surface to deform. So in using a model that simulates changes in pressure and volume changes at depth and linking it to calculate the expected surface deformation from those changes, I can simulate what the uplift data might look like for that chamber. Then, comparing that simulated data to the real data I can extract new information about the magmatic system.

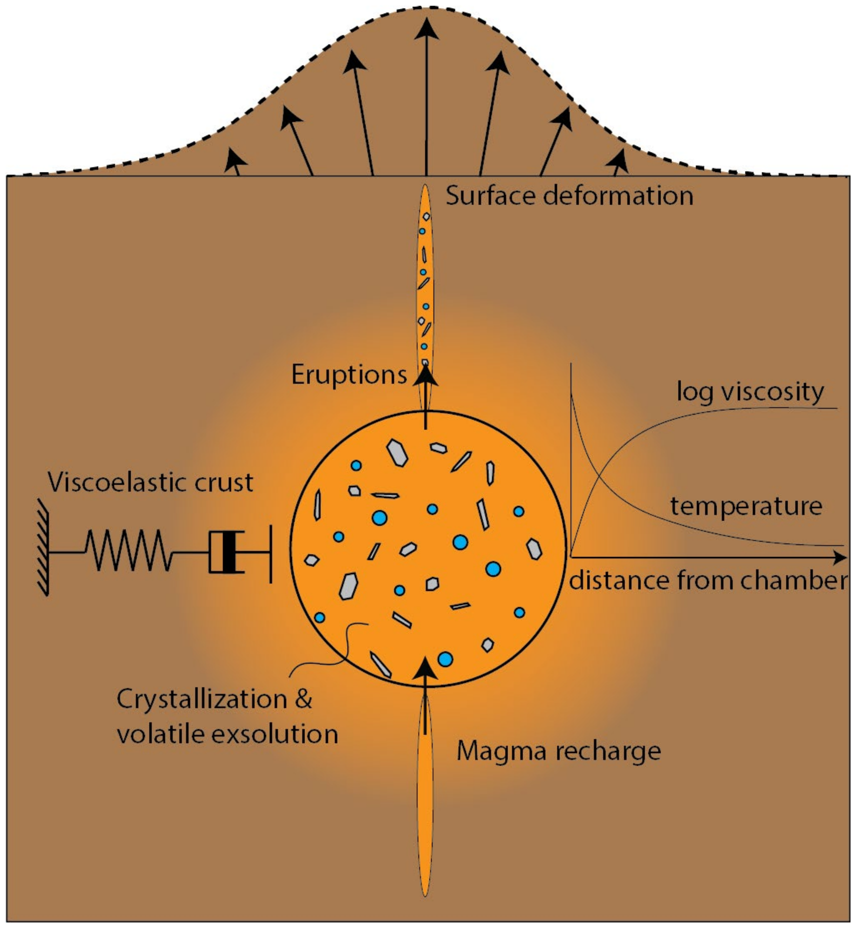

Figure 7: Conceptual figure of the magma chamber model

A conceptual figure of all the considerations used to estimate surface deformation within the model. A spherical magma chamber in a viscoelastic crust is subject to time-dependent recharge, cooling, crystallization, and volatile exsolution (from Townsend, in review).

To simulate the surface deformation observed at South Sister, I used a model for a magma chamber that was linked to surface deformation. For this project, I chose a model for a spherical magma chamber in a viscoelastic crust subject to time-dependent recharge, cooling, crystallization, and volatile exsolution (Degruyter and Huber, 2014). This model was then linked to a model of surface deformation of a spherical source in a viscoelastic half-space (Segall, 2010; Bonafede and Ferrari, 2009). This model predicts vertical and radial displacements at the surface due to a volume change occurring in a spherical chamber at some depth beneath the surface. The model used also allows for the experimentation of different recharge conditions as well as no recharge. The three possible conditions are constant recharge, a recharge pulse (with the rate of recharge beginning gradually, reaching some peak, then tapering off again), or recharge due to a pressure difference between an upper chamber (the modeled chamber) and a lower chamber (Reverso et al., 2014).

To model a complicated feature, such as a magma chamber, some assumptions were made to make the model efficient. Firstly, this model assumes that the magma chamber is spherical. There has been a lot of debate on the shape of South Sister's magma chamber but Rodríguez-Molina et al. (2021) (the most recent paper published on the subject) concludes that while other shapes are possible the difference in how well the data are fit by different geometries is minimal. They also state that in the absence of large differences between geometries that the chamber can be estimated to be a sphere, as it is the simplest shape. I also assume that the chamber is homogenous, is in equilibrium, and the crust around it is thermally "mature". Assumptions are also made about the magma within the chamber. It is assumed that the magma within the chamber is a dacite and the relationships between temperature and crystal fraction are tuned to that composition. South Sister has erupted mostly rhyolitic and intermediate magmas so it is possible to erupt dacite there, but it is unknown what the composition of the magmas within the chamber are (Fierstein et al., 2011). The relationships between pressure and water solubility, and the composition of volatiles have also been simplified to streamline the model. In this model, the only possible volatile is water, but in reality other volatiles such as CO_2 may affect chamber parameters.

Traditional surface deformation models typically do not consider the physics of magma recharge and other magma processes, nor do they consider causes of the exponential decay in uplift, which was observed at South Sister and elsewhere. By linking surface deformation to the underlying magmatic processes and physical properties of magma, I can place tighter constraints on valuable parameters such as the magma chamber volume and volatile content, and I can test competing hypotheses about the role of time-dependent magma recharge vs. viscoelastic effects on the exponential decay of surface uplift.

The Markov-Chain Monte Carlo (MCMC) Algorithm

The magma chamber model that I am using predicts how much surface deformation would occur during magma recharge of a certain magnitude and duration to a magma chamber with a certain depth, volume, and water content. This simulated surface deformation from the model output is then compared to the actual surface deformation data, collected through InSAR and GPS, to determine how well the data sets match. This comparison is then used to determine the likelihood of the model parameters used to simulate the magma chamber and recharge conditions.

A Markov-Chain Monte Carlo (MCMC) algorithm was used to estimate magma chamber and recharge parameters for the deforming part of the South Sister system. This algorithm works by completing a series of random walks in parameter space using a defined step size within some bounded range (Anderson et al., 2013). The range in which the algorithm was allowed to experiment was determined by prior information about the South Sisters magma chamber. The MCMC starts with some random combination of values within the ranges and calculates the surface deformation provided by those values. That is then compared to the actual deformation data and a likelihood for those values is produced. The algorithm then takes a random step (as determined in the step size) from those first values to produce a new "candidate" set of model parameters and calculates the predicted surface deformation using the candidate model. The likelihood of the candidate model is calculated and compared to the previous model. If the likelihood of the candidate model is greater than the likelihood of the previous model, then the MCMC keeps the candidate and continues to step from that direction. If the likelihood of the candidate model is worse, it may still be kept if the ratio of the likelihood of the candidate compared to the previous model is greater than a randomly generated number between 0 and 1. Keeping a random number of candidate models that do worse prevents the MCMC from getting stuck in "local" best-fit solutions and allows the MCMC to find the "global" best-fitting set of model parameters. If the candidate model is not kept, the algorithm returns to the previous position and tries again with a different step. This continues until the algorithm has completed a set number of these steps. The more steps you allow the MCMC, the greater the probability that the MCMC converges to a maximum likelihood.

The parameters that the MCMC tested were: the size and depth of a magma chamber, location of the chamber (in terms of latitude and longitude), the magmatic water content, and the magma recharge conditions (the onset, duration, and peak rate of recharge). These were chosen to be free parameters because there is either not a consensus on that aspect of the chamber, or these parameters have not been modeled before at this location.

Results

Model Set-Up

The MCMC was run for a spherical magma chamber in a viscoelastic crust with a pulse-like recharge event. There were 56 chains and they each completed 1,500 iterations. This is a low number of iterations, and in the future I hope to run the MCMC again with many more iterations. Figure 8 shows the burn in of the most likely chain (29) followed by the convergence of the MCMC on the most likely answer, which was iteration 1,293.

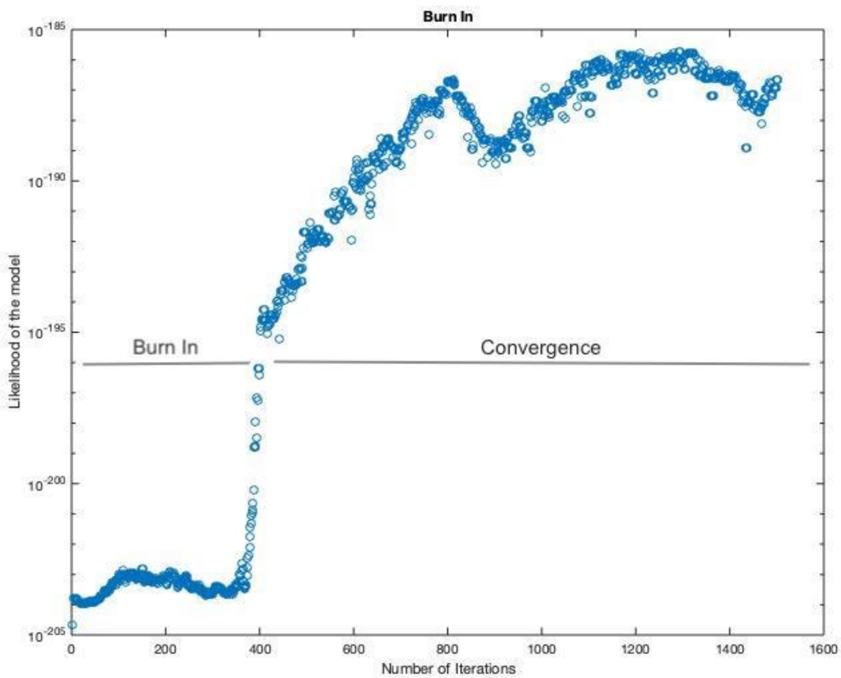

Figure 8: Burn in for the most likely chain

The likelihood of each iteration within the chain as it worked towards completing its 1,500 iterations.

The model was run twice, once with a larger step size, and once with a smaller step size. The results produced by the smaller step size were less likely than the larger step size. This was due to the same number of iterations for both models, allowing the larger step size model to cover more "ground" than the other. In the long term, the larger step size model will lose detail due to the larger step size, but for this project it provided sufficient results. All the results below will be from the outputs produced by the larger step size model.

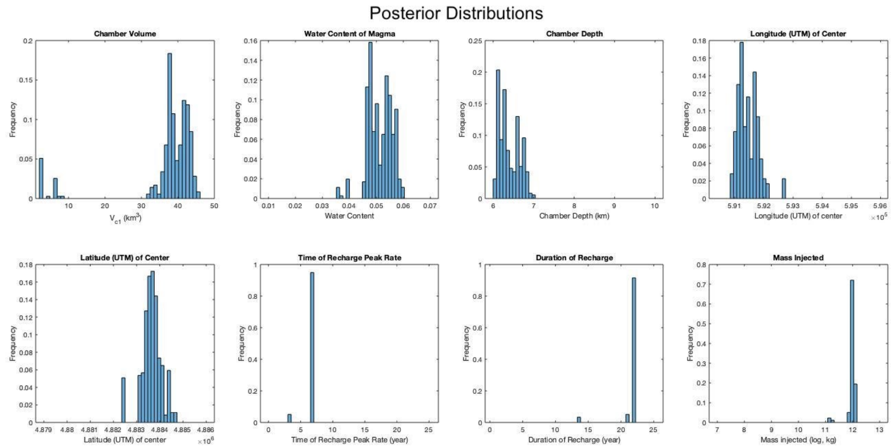

Figure 9: Posterior distributions of the “free” parameters in the MCMC.

The x-axis of each sub-figure represents the range that the MCMC was allowed to test over.

While the MCMC was allowed to test many different variables, each within a preset range, it seems that the algorithm had clear preferences. The x-axis of each plot in figure 9 is one of the variables I allowed the model to test over. Ideally, the plots in figure 9 would have a gaussian shape to them, but due to the limited number of iterations I allowed they have a weak gaussian shape, if any at all. The ranges that each variable was allowed to test within were determined by previous estimations of South Sister’s magma chamber and general estimations of magma chambers. All of the variables were modeled independently of each other, but in reality these variables would be dependent on each other. The burn in for these estimations has been removed for the posterior distribution plots, only results with a likelihood within a certain range were plotted.

InSAR

The real surface deformation data that was used as a comparison to determine the likelihood of a certain set of variables came from three different InSAR satellites:

the first being ERS-1 and ERS-2 (1995-2001), the second is Envisat (2003-2010), and the third is Sentinel-1 (2015-2020). After being processed these three satellites resulted in three different qualities of the LOS deformation data, ERS-1 & 2 provided the highest amount of coherence followed by Envisat and Sentinel-1. Over its 6-year interval ERS-1 & 2 provided 19 usable interferograms each with high coherence. Envisat was used over a 7-year interval and it also provided 19 interferograms, but with a lower overall coherence than ERS 1 & 2. Sentinel-1 was used over the most recent 5 years and provided the worst overall coherence and 16 interferograms. The overall loss of coherence of the satellites, which can be seen in figure 10, as time went on is believed to be from the decreasing rate of the uplift event. Presently, the uplift appears to be around ~0.5 cm/yr which is much lower than the peak uplift rate of ~3-4 cm/yr between ~1998-2004.

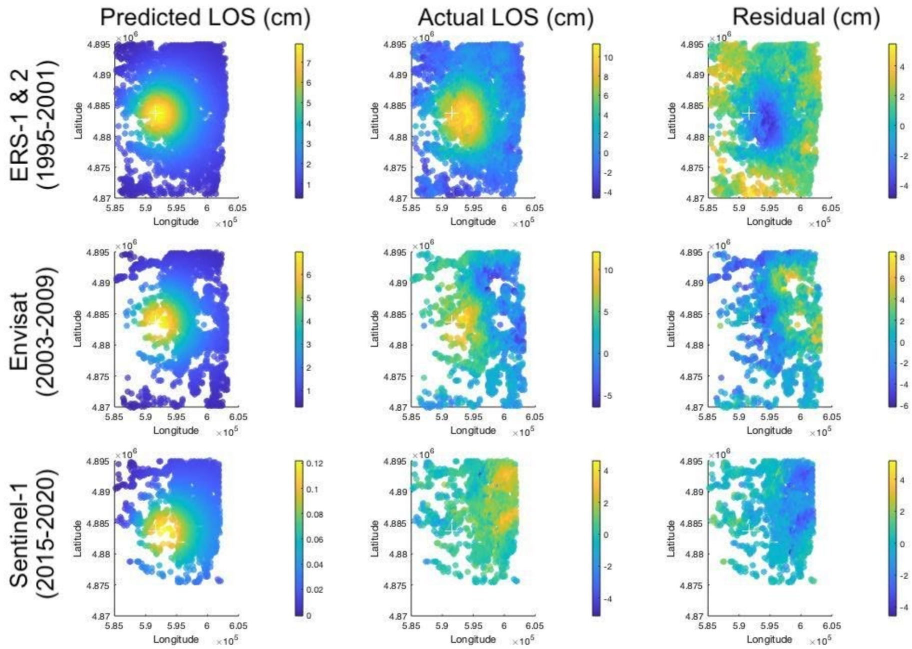

Figure 10: Model outputs for InSAR

The left column is the predicted LOS displacement from the best fitting magma chamber model, the center column is the actual LOS InSAR data, and the right column is the residual between the two. The top row is all the products for the ERS-1 & 2 satellites, the middle row is Envisat, and the bottom row is Sentinel-1. The white + on each plot shows the best fit center of uplift by the model.

Spatially, the pattern of LOS displacement is fairly consistent across all three satellites. There appears to be a mostly circular pattern of uplift, most obvious in the LOS data from ERS 1& 2, but it is slightly elongated in the north/south direction. This elongation has also been noted by Rodríguez-Molina et al. (2021) in their analysis and kinematic modeling of this event. Since I am only testing one chamber geometry, a sphere, the simulated LOS data is circular across all three satellites. The elongation of the actual data can also be seen in the residuals, which is the difference between the actual and simulated displacements. For ERS-1 & 2, the model over-predicted the LOS displacement within the region of uplift while under predicting the surrounding region.

The residual for Envisat has the largest difference between the actual and simulated data, mostly around the Sisters themselves. The under-prediction of LOS deformation there is probably a false signal of uplift at the Sisters due to the influence of gravity waves. This false uplift can also be clearly seen in the actual LOS data from Sentinel-1, with almost 4 cm/yr of uplift being recorded at the Sisters. The growth in the influence of gravity waves as the time moves on can be attributed to the decreased rate of uplift and decreased coherence with each satellite.

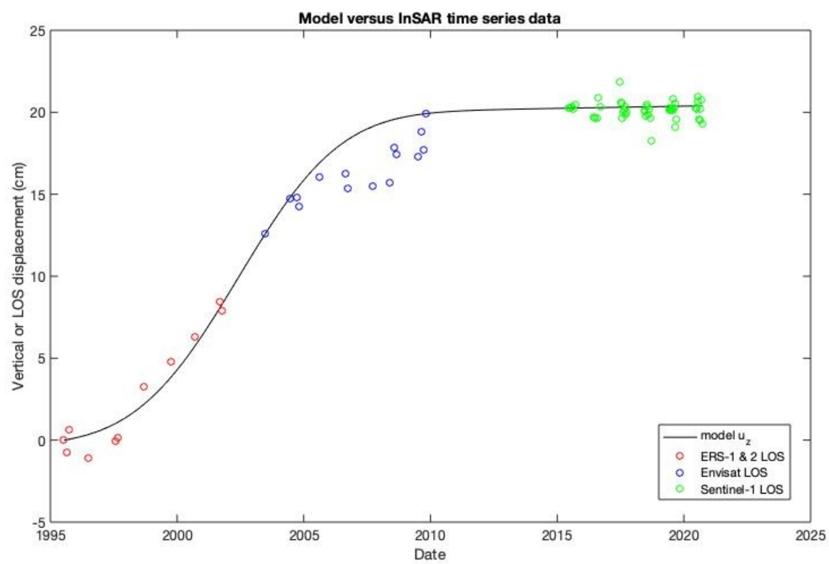

Figure 11: Model versus InSAR time series data

A comparison between the simulated vertical displacement data from the model (black line) and the LOS time series of ERS-1 & 2 (red), Envisat (blue), and Sentinel-1 (green).

The decay in the rate of uplift is clearly seen in the actual data like in figure 6 and figure 10. For each satellite I also created a LOS time series and compared the actual time series to the simulated one (figure 11). As identified in the ERS-1 & 2 LOS time series there was a gradual start then rapid acceleration of the uplift event, and by the time Sentinel-1 is being used the rate has decayed. The simulated time series does capture both of these changes in the rates of uplift throughout the lifetime of this event. The rapid decay of the deformation rate falls during the time of Envisat, and the Envisat data does not appear to fit well with the simulated time series curve. This may just be from a poor fit with the model parameters used to simulate this time series (the simulated data is from the model run with the highest likelihood, that does not mean it is perfect). Two ways to possibly have the Envisat fit better with the simulated time series could be to allow further iterations and/or a smaller step size when running the MCMC algorithm, or utilizing the GPS data which provides data for the gaps between the satellites allowing for a much higher temporal resolution.

Best Fitting Chamber Conditions

The MCMC algorithm found the best fitting chamber to have a volume of 38 km^3 at 6 km depth. The model had a preference for shallow chambers, as can be seen in figure 8, where the posterior distribution is only within 6-7 km depth despite being allowed to test from 6-10 km depth. This preference towards shallow chambers also led to a preference towards larger chambers to compensate for the observed uplift. The best fit chamber model also has a water content of 4 wt. %. The MCMC was also set up to test for pulse-like recharge, where the best-fit amount of magma emplaced was 1×10^{12} kg over the duration of the recharge. The pulse was predicted to last for ~15 years with a maximum recharge rate of ~4,000 kg/s occurring ~7 years after the beginning of the recharge event. Due to the magma emplaced by the recharge event the pressure within the chamber rose ~6 MPa. The model also predicted the pressure increase to be delayed from the pulse of magma recharge.

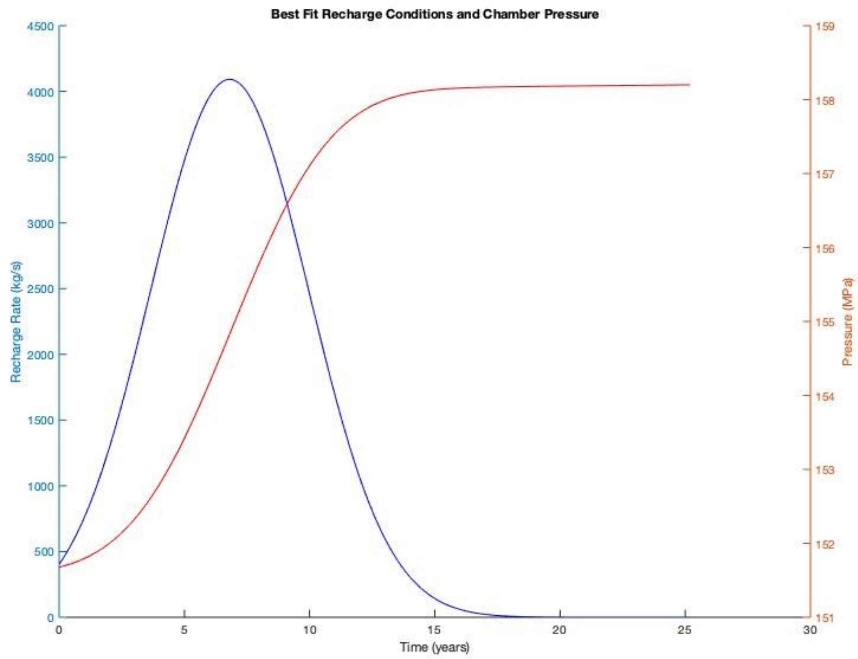

Figure 12: Best fit recharge conditions and chamber pressure

Shows the relationship between the best fit recharge conditions (blue) and the resulting change in chamber pressure (red).

Discussion

Interpretation

During my modeling of this event, I was not addressing the geometry of the source of uplift, only some kinematic aspects (size, depth, location, etc.) and some physical processes (wt. %, recharge conditions, etc.). As previously established, there has been much debate about the geometry of the magma chamber but all papers have mentioned a sphere as a possible source of inflation. And with the most recent paper concluding that a sphere is the best geometry to model with for its simplicity and lack of large error differences when compared to asymmetrical sources, I believe that my use of a spherical magma chamber model can provide valuable new information about the physical processes, which have not been modeled at this location before (Rodríguez-Molina et al., 2021). The estimation by Rodríguez-Molina et al. (2021) estimated a spherical magma chamber at 4.5-6 km depth and my estimation was at 6 km depth but the posterior distribution of the MCMC (figure 9) showed that my model did prefer shallow chambers. Both Rodríguez-Molina et al.'s and my findings indicate a shallower chamber which is corroborated by Riddick and Schmidt (the second most recent paper estimating South Sister's magma chamber) which places the chamber at ~5-7 km depth (Rodríguez-Molina et al., 2021; Riddick and Schmidt, 2011). In future estimations of South Sister's magma chamber, I will adjust the bounded range with the MCMC of the chamber depth to include values shallower than 6 km as a shallow chamber seems to be a more likely solution.

As the physical properties of the magma chamber have yet to truly be explored by many, there cannot be much comparison to previous literature on the topic (at this location). Rodríguez-Molina et al. briefly discusses their belief that this uplift is caused by magma recharge that began between October 1998 and August 1999, and Riddick and Schmidt believe a recharge event began between June 1996 and July 1997 (Rodríguez-Molina et al., 2021; Riddick and Schmidt, 2011). My estimation of the recharge event places its start date before the initial detection of uplift in 1996. This would indicate a delay between the start of a magma recharge event and deformation at the surface. I have previously discussed the delay of pressure increase in the chamber from the magmatic injection, which can be seen in figure 12, and the delay in surface deformation from the start of magma injection appears to follow a similar trend. This delay in both surface deformation and pressure increase could be due to physical properties of the magma itself, such as its volatile content and compressibility. A highly compressible magma might show similar delays in deformation of the crust and pressure change.

At South Sister there is also an exponential decay in the rate of uplift starting in ~2005 which I attempted to explain in this modeling. My model took into account the viscoelastic relaxation of the crust which I believe to be the main driver in the exponential decay of the uplift rate. The magma recharge pulse is estimated to have ended in 2010 (~15 years after 1995) but there is still ~0.5 cm/yr of uplift being recorded at South Sister, so I believe that this is due to a viscoelastic response of the crust after the magma emplacement.

Broader Impacts and Future Work

The overarching aim of this project is to link patterns of surface deformation to changes occurring in an underlying magma chamber. To achieve this goal, I looked at the ongoing uplift event at South Sister, and in doing this work I have been able to constrain the kinematic aspects and physical processes occurring within South Sister's magma chamber. The more we know about these aspects of any magma chamber the better we will be able to predict whether a surface deformation event is indicative of an eruption. This project focused on constraining the magma chamber under South Sister since this is a recent uplift event that has not yet culminated in an eruption. Despite South Sister not erupting and the uplift event decaying in rate, Three Sisters is still listed as being a "Very High" threat according to the USGS (Ewert et al., 2018). And since surface deformation data is widely available and accessible to everyone, the methods and results of this project can be easily applied to other volcanoes with recorded surface deformation.

In the future I hope to further explore this uplift event while using all available data sources. Currently, the modeling of the magma chamber only incorporated InSAR data and used GPS as an external test on the InSAR data. The continuous GPS data since 2001 will be able to provide much needed information between the different satellites' data, thus improving the accuracy of the model. Further into the future, I also hope to incorporate the volcanic history of South Sister into the modeling process. Since the magma chamber model was originally created for magma chamber evolution I can model over a longer timescale (e.g. several thousand to tens of thousands of years) and consider long-term changes within the magma reservoir constrained by petrologic and geochemical data from past eruptive deposits. Eventually, I also hope to be able to apply this model to other volcanic systems and surface deformation events, possibly even deformation events that culminated in an eruption like the current eruption at Fagradalsfjall, Iceland, to gleam more information into their magma chambers.

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