Ground deformation occurring in the city of Auckland, New Zealand, and observed by Envisat interferometric synthetic aperture radar during 2003–2007

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[1] In this study we present modeling results derived from ground deformation observed in the Auckland Volcanic Field (AVF) by the C-band Envisat Synthetic Aperture Radar. Auckland, the largest city in New Zealand with a current population of over one million, coincides with the AVF, which comprises about 50 individual, largely monogenetic, basaltic volcanoes distributed across a total area of 360 km². The most recent and largest eruption there occurred 600 years ago. While it is anticipated that the chance of any existing volcano reawakening is very low, a new volcano could be created at any time in a new location within the field. The aim of this work is to evaluate the feasibility of interferometric synthetic aperture radar (InSAR) for mapping ground deformation associated with magma ascent, which would be a likely precursor to the onset of volcanic activity. For this study we acquired and processed 23 single look complex (SLC) images from the Envisat satellite (Track 151, Frame 6442, IS2, VV) spanning from July 2003 until November 2007. All possible combinations of differential interferograms were created. Stacking, Small Baseline Subset (SBAS) and Permanent Scatterers (PS) processing algorithms were used to determine spatial and temporal patterns of surface deformation as well as their average rates. A number of localized deformation regions were consistently observed by all three techniques. Due to a lack of evidence pointing toward a relationship with volcanic or tectonic sources it was assumed that they are produced by groundwater withdrawal and recharge. Three largest regions of subsidence (S1–S3) and also three largest regions of uplift (U1–U3) were modeled with the derivative-free simplex algorithms for location, depth and source volume change using a Mogi point source approximation. The results show that InSAR is a viable technique capable of detecting the scale, rate and spatial distribution of precursory deformation that would likely be associated with resumption of volcanic activity in the Auckland urban area.


1. Introduction

[2] One of the key challenges faced by volcanologists is the improvement of our understanding of when and where the next eruption will occur, particularly in the case of quiescent volcanic centers which may have been dormant for a very long time and currently exhibit no signs of unusual activity. At such volcanoes, eruptions are infrequent on human time-scales, and the associated hazards may be poorly acknowledged, inviting encroachment by populations and increasing the risk of future disasters. Recognition that a volcano is merely the surface expression of a deep-seated cyclical magmatic process enables the use of three different monitoring techniques to detect possible indicators of deep and hence long-term unrest: earthquakes [McNutt, 1996]; magmatic CO₂ flux rates [Salazar et al., 2000; Hernandez et al., 2000]; and aseismic surface deformation. A range of geodetic tools can be used for monitoring surface deformations including interferometric synthetic aperture radar (InSAR), large-aperture GPS surveys, microgravity surveys, dense continuous GPS arrays, strainmeters and tiltmeters [Dzurisin, 2003]. InSAR has become an important part of volcano monitoring worldwide since its first application at Mount
Etna [Massonnet et al., 1995]. The technique relies on combining phase information from two or more SAR images of the same area captured at different times from a similar vantage point to produce an interferogram [Massonnet and Feigl, 1998]. This shows range changes in the view direction between the satellite-borne instrument and the Earth’s surface, and can be further processed with a topographic model to image ground deformation at a horizontal resolution of tens of meters over areas of ∼100 × 100 km with cm to sub-cm vertical precision under ideal conditions. The broad areal extent and high vertical resolution of spaceborne InSAR is particularly valuable for study of deformation signals at volcanic fields and calderas [e.g., Lu et al., 2000; Kwoun et al., 2006] where there is considerable uncertainty about where activity may be focused or at complex volcano-tectonic systems characterized by lateral as well as vertical magma migration [e.g., Lu et al., 2002].

1.1. Auckland Volcanic Field

[3] The Auckland Volcanic Field (AVF, Figure 1) comprises 49 small basaltic volcanoes spread across an elliptical area of ∼360 km² [Allen and Smith, 1994], which have erupted through a ∼500 m thick cover of Miocene and Plio-Pleistocene marine sedimentary rocks that overlie faulted Mesozoic basement [Edbrooke et al., 2003]. The field has been active for circa 140,000 years, producing ∼3.4 km³ (Dense Rock Equivalent, DRE) of basaltic eruption products [Kermode, 1992; Smith and Allen, 1993], with the most recent eruption occurring only 600–800 years ago. Eruptions have ranged in style from phreatomagmatic (producing tuff rings and maars) to magmatic (forming scoria cones and lava flows), with individual vents often generating several styles of activity [Allen and Smith, 1994]. Each vent typically erupts a single batch of magma during a discrete, relatively short-lived eruption episode that lasts for less than ten years, although there is increasing evidence for episodes that involve eruption of a magma batch at multiple adjacent vents over periods of centuries [Allen and Smith, 1994; Cassidy et al., 1999; Cassidy and Locke, 2004]. Most centers have eruptive volumes less than 0.01 km³ (DRE), six have volumes of 0.05–0.35 km³, while the most recent eruption, Rangitoto in circa 1350 A.D., produced approximately 2 km³ of magma (59% of the AVF total). The source of the basaltic magma is thought to lie at depths of 70–140 km, based on mantle xenoliths in erupted material [Cassidy et al., 1986], U-Th isotopes [Huang et al., 1997], and seismic detection of a low velocity layer [Horspool et al., 2006]. The presence of mantle xenoliths was used to estimate a magma ascent rate of 1–10 cm/s [Cassidy et al., 1986], implying rise from a depth of 100 km in 10–100 days. Historically low levels of seismicity in the area suggest that, by analogy with other monogenetic basalt fields, seismic precursors could occur as soon as a few days to 2 weeks before an eruption [Sherburn et al., 2007].

[4] Further eruptions from the AVF are likely, with serious social and economic consequences for the city of Auckland [Johnston et al., 1997; Paton et al., 1999; Magill and Blong, 2004].
in the Auckland Volcanic Field associated with magma ascent that would be a likely precursor to the onset of volcanic activity.

2. Data and Processing Techniques

[7] In order to study ground deformation in the Auckland Volcanic Field we acquired and processed 26 Envisat ASAR (Track 151, Frame 6442, IS2, VV) images spanning from 18 July 2003 until 9 November 2007 (Table 1). The GAMMA interferometric processor [Wegmuller and Werner, 1997] was used to compute differential interferograms. Precise orbits from the European Space Agency and Delft University were used to estimate orbital parameters and the 90 m SRTM Digital Elevation Model (DEM) [Farr and Kobrick, 2000] was used to remove the topographic phase. Initially all images were re-sampled to a single master image acquired on 17 June 2005 (20050617), 2 × 10 multilooking to a resolution 20 × 40 m (range x azimuth) was applied and then differential interferograms were calculated. All interferograms with slave images acquired on 20031205 were removed from further processing because of a large error in the estimation of orbital parameters. Phase unwrapping was performed using the Minimum Cost Flow algorithm [Costantini, 1998], and least squares estimation of interferometric baselines was performed in order to correct for minor errors in estimation of orbital parameters. Computed differential interferograms were then used for advanced processing and final results were geocoded and plotted.

[8] Initial interpretation of 117 differential interferograms revealed the presence of significant tropospheric noise on most interferograms and the absence of a large deformation signal. In order to improve the quality of these results we applied three advanced processing techniques: stacking, Small Baseline Subset (SBAS) and Permanent Scatterers (PS). Since the atmospheric noise is random in time and space while ground deformation is consistent, advanced processing by any of the proposed techniques decreases the contribution of random noise, increasing the accuracy of ground deformation measurements [Samsonov, 2010].

2.1. Stacking

[9] For stacking analysis [Wright et al., 2004; Sandwell and Price, 1998] it was initially assumed that the average rate of deformation across the whole region is zero. All 117 interferograms with baselines less than 400 m were shifted to meet this criterion and an initial stack was calculated. Second, a stable region (16 × 16 pixels) was chosen and the stack with corresponding errors was recalculated from interferograms adjusted against this reference point. Multiple reference points were tested but results did not vary significantly.

2.2. Small Baseline Subset

[10] For SBAS analysis we used the methodology provided by Berardino et al. [2002] and Samsonov [2010]. The processing code for this technique was written in MATLAB.

Table 1. Envisat ASAR Images Spanning 2003–2007 Used in This Study and the Time Span in Days From the First Acquisition

<table>
<thead>
<tr>
<th>Image</th>
<th>Time</th>
<th>Span</th>
</tr>
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</tr>
<tr>
<td>2</td>
<td>20030926</td>
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</tr>
<tr>
<td>3</td>
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<tr>
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<td>1575</td>
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</tbody>
</table>

*The image acquired on 20031205 had a large orbital error and was removed from further processing. Time is given in YYYYMMDD format.
because of the simplicity of the matrix computation. The same 117 interferograms ($B_p < 400 \text{ m}$) were used to create a set of 117 equations with 25 unknown velocities ($v_i$). The solution was calculated only for pixels that were coherent ($g > 0.3$, where $g$ is a magnitude of cross-correlation between master and slave images calculated for each pixel) on all interferograms. The displacement time series were reconstructed from known velocities provided by SBAS and time intervals [Kwoun et al., 2006] and linear regression was performed in order to estimate the average linear deformation rates for the 2003–2007 period. RMS errors were also calculated for each pixel as an average deviation from the linear trend.

2.3. Permanent Scatterers

[11] Permanent scatterers [Ferretti et al., 2001, 2004] were identified as pixels with the dispersion of intensity less than 0.25, and further processing was performed on permanent scatterers only. A single master was chosen (20050617) and 24 interferograms were calculated. However, a few interferograms had large perpendicular baselines and, therefore, could not be visually examined due to the $2\pi$ ambiguity in unwrapping. Several other interferograms had a very strong residual orbital signal. These were removed from the consequent analysis. Regression analysis then was performed to estimate linear rates of deformation using baseline and time dependence data of the interferometric phases. The deviation of the phase from the regression fit was used as a goodness-of-fit parameter and only certain pixels with lower deviation than a set threshold value were selected. Various threshold values were tested experimentally and the best value based on visual observation of the results was chosen. However, the analysis of the residuals even for the best case revealed multiple errors in unwrapping caused by large atmospheric noise and errors in the DEM.

[12] Instead, the processing algorithm was slightly modified. Only interferograms with perpendicular baselines less than 300 meters were selected and Ground Control Points-corrected orbital parameters were copied from similar pairs used in stacking and SBAS processing. Then the topographic phase was removed using the SRTM DEM, followed by phase unwrapping using a Minimum Cost Flow algorithm [Costantini, 1998]. Finally, seventy-eight unwrapped differential interferograms with corrected orbital parameters were used in the regression analysis for estimation of linear deformation rates with corresponding errors.

3. Results

[13] The results of the interferometric processing consist of 117 differential interferograms used in stacking and SBAS processing and 78 differential interferograms used in PS processing (Figure 2), average linear deformation rates calculated with stacking, SBAS and PS techniques with corresponding errors, and time series calculated with SBAS and PS techniques. Initial interpretation of 117 interferograms revealed a significant amount of tropospheric noise and absence of a large deformation signal. Some deformation signal retrospectively was observed on a few interferograms; however; during the initial analysis it was interpreted as noise.
3.1. Stacking

[14] Results of stacking are presented in Figure 3a with corresponding errors in Figure 3b. Epicenters of historic earthquakes (prior to 2003) are plotted as black dots. Only the urban area of the Auckland Volcanic Field (AVF) is coherent on most interferograms. Overall the whole region is stable within 1–2 mm/yr and no large scale deformation signal is observed. However, a few regions of localized subsidence and uplift are apparent. Three well defined areas of subsidence are observed with deformation rates of about −0.4 cm/yr located at S1:(S36.89, E174.63), S2: (S36.94, E174.84) and S3:(S37.03, E174.93). The two smallest subsidence signals (S1 and S2) are only about 1 km in diameter. The larger subsidence located at the southern part of the map (S3) is approximately 5 km in diameter. Three large uplifts are also observed in the region located at U1:(S36.98, E174.88), U2:(S36.94, E174.66) and U3:(S36.91, E174.69) with the rate of deformation approximately 0.35–0.4 cm/yr. The uplift U1 is the largest with dimensions 4 by 8 km. It has a well defined southwest to northeast trend with an apparent maximum at the northwest corner. Uplift U2 is approximately 3 km in diameter and only partially visible due to decorrelation. Uplift U3 is smaller, about 1 km in diameter.

[15] Standard deviation of the stacked deformation rates ranges from about 0 to 0.2 cm/yr, reaching a minimum value at the region chosen as a reference and increasing with distance from that point. This behavior is anticipated because of residual orbital and other long wavelength errors. A few disconnected regions have larger error than the main area due to errors in phase unwrapping.

3.2. Small Baseline Subset

[16] SBAS deformation rates are presented in Figure 4a, and in general, they are in good agreement with the stacking results. All three region of subsidence (S1–S3) are still clearly visible with approximately the same rates of −0.4 cm/yr. However, some scattered subsidence is also observed in the northern part of the image. Uplift U1 is visible but with smaller rates of ∼0.2 cm/yr, and uplifts U2 and U3 are approximately the same as on the stacking image. The error was calculated as an RMS deviation from linear trend [Press et al., 2007] and its value does not vary significantly within the image, excluding a few disconnected area probably affected by errors in phase unwrapping.

[17] Results of time series analysis performed using the SBAS technique [e.g., Kwoun et al., 2006] without spatial averaging or temporal filtering area are presented in Figure 5. Rates of deformation were calculated for 25 temporal points spanning 2003–2007 and then cumulative deformation was reconstructed by integration. The time series analysis reveals deformation with a similar overall trend pattern for most sources except subsidence S1, which shows some sign of reversal after April 2006. Large fluctuations are observed on
all six time series, which are probably caused by seasonal signal or tropospheric noise.

3.3. Permanent Scatterers

[18] PS deformation rates are presented in Figure 6a with corresponding errors in Figure 6b. In general agreement between this and previous results is reasonable. Subsidence S1–S3 are still clearly visible with approximately the same rates as above. The uplifts U1 and U2 are hard to distinguish from noise but uplift U3 is somewhat apparent. Standard deviation ranges from about 0 to 0.2 cm/yr and its value increases with distance from the reference region. It is apparent that the magnitude of the observed ground deformation is similar to the error of measurements. The accuracy might be improved if data covering a longer time period becomes available. Because of lower accuracy the PS results were not used in further modeling and inversion.

3.4. Mapping Volcanic Deformations

[19] In order to evaluate the applicability of InSAR for the detection of volcanic deformation in AVF, in Figure 7 we plot maximum vertical displacement that would be produced by a volcanic source (Mogi point source approximation) of various strengths. Each line in Figure 7 correspond to a source located at different depth - 0.5, 1, 4, 8, 16, and 32 km plotted using a log-log scale in order to capture a large range of source strengths 103–109 m³ (horizontal axis) and a range of observable ground deformation 0.1–100 cm (vertical axis). It seems that 1 cm of surface ground deformation is detectable with C-band InSAR in the absence of significant tropospheric noise, which can be produced by sources at various depths depending on their strength. For example, an intruded volume of 107 m³, typical of small AVF eruptions, would be detectable by InSAR at depths less than 15 km, while a volume of 108 m³ should be detectable at much greater depths. Because the Mogi model assumes an elastic media, the detectable depth for 108 m³ is limited by a crustal thickness at approximately 25 km. Finally, in order to provide real-time InSAR detection of magma intrusion, InSAR images would have to be acquired at a three days repeat cycle, assuming a magma ascension rate of 1–10 cm/s, which is not available under the present satellite configuration. Therefore, detection and monitoring of magma ascent in the AVF region, including estimation of the size and depth of volcanic hazard is possible using current SAR satellite technology and InSAR processing capability, while ascent monitoring would require additional satellite coverage.

4. Modeling Observed Signal

[20] The observed ground deformations were inverted in order to derive source parameters and in particular source location, strength and depth using a Mogi point source embedded in an elastic half-space approximation [Mogi, 1958]. The aim of the inversion was to determine if the observed deformations were caused by volcanic activities.
or they are anthropogenic, potentially caused by groundwater withdrawal and natural recharge followed the cessation of withdrawal. Because of the spatial extent of the deformation, shallow sources were assumed and a Poisson’s ratio of 0.25 and an elastic shear modulus of 10 GPa were chosen, to account for the less compacted and rigid material present at shallower crustal depths. Due to the best spatial coverage and the smallest error only stacking results were used in the inversion. The radial and vertical displacements caused by Mogi-type source are described by the following equations:

\[ u_r = \frac{3a^3 \Delta P}{4\mu} \frac{r}{R^3}, \quad u_z = \frac{3a^3 \Delta P}{4\mu} \frac{d}{R^3}, \]  

Figure 5. (a) Time series analysis of subsidence s1:(S36.89, E174.63), s2:(S36.94, E174.84) and s3: (S37.03, E174.93) and (b) uplift regions u1:(S36.98, E174.88), u2:(S36.94, E174.66) and u3:(S36.91, E174.69), calculated using SBAS technique. No spatial averaging or temporal filtering was performed on the time series.
where $u_r$ and $u_z$ are the radial and vertical displacements, $a$ is the source radius and $\Delta P$ is the pressure change, $\mu$ is the shear modulus, $r$ and $d$ are the radial distance of the observation point and source depth. Due to the linear relation between source radius and pressure change in the deformation kernel of the isotropic point source it is possible to measure only the total change of $a^2 \Delta P$. Instead it was proposed to reformulate the Mogi model according to Tiampo et al.

![Figure 6](image1.png)

**Figure 6.** (a) Linear rates of deformation with (b) corresponding errors calculated from 78 differential interferograms with $Bp < 300$ m acquired by the Envisat satellite between 2003 and 2007 using Permanent Scatterers technique.

![Figure 7](image2.png)

**Figure 7.** Maximum surface displacement for Mogi-type point sources [Mogi, 1958] due to volume change located at various depths between 0.5 and 32 km. Log-log scale is used.
[61x374](2000) to relate the ground deformation to the source volume change:

\[ u_r = \frac{3 \Delta V}{4\pi R^3} \]

where \( \Delta V \) is the volume change.

### 4.1. Nonlinear Inversion Using the Derivative-Free Simplex Method

The four model parameters (longitude, latitude, depth and volume change of the source) were estimated by minimizing the misfit function between observed ground deformation calculated by stacking (Figure 3a) and values provided by the Mogi model [Mogi, 1958] using the derivative-free simplex method [Nelder and Mead, 1965]. The misfit function used in this study was a common L2-norm (the root square of the sum of square errors, RSSE). The inversion for each source was repeated one hundred times and the average value and standard deviation for each modeled parameter were calculated. This approach allowed us to estimate the accuracy of the inversion. In order to decrease inversion time the following limitations were applied to the modeled parameters: longitude and latitude were bounded to ±1 km from the center of the surface deformation anomaly, depth varied from 200 to 2000 meters and volume change from 0 to 10^6 m^3 for the uplift signals and 0 to −10^6 m^3 for the subsidence signals.

The results of this modeling, source location, depth and volume change, are presented in Table 2 and in Figure 8. Three regions of subsidence were modeled by four point sources. Subsidence S1 was modeled as a point source located at depth 451 m with volume change \(-4174 \text{ m}^3/\text{yr}\); subsidence S2 was modeled as a point source located at depth 587 m with volume change \(-3859 \text{ m}^3/\text{yr}\); and subsidence S3 was modeled as two point sources located at depth 715 and 1101 m with

### Table 2. Results of Computer Modeling Using Mogi Point Source Approximation

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<tr>
<th>Source</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Easting (km)</th>
<th>Northing (km)</th>
<th>Depth (m)</th>
<th>Volume Change (m^3/yr)</th>
<th>RMSE (cm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>174.649955</td>
<td>-36.888961</td>
<td>-10.348 ± 0.001</td>
<td>12.313 ± 0.001</td>
<td>451 ± 1</td>
<td>-4174 ± 1</td>
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<td>S2</td>
<td>174.825482</td>
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<td>7.237 ± 0.318</td>
<td>587 ± 144</td>
<td>-3859 ± 1029</td>
<td>3.03</td>
</tr>
<tr>
<td>S3 (W)</td>
<td>174.939379</td>
<td>-37.021722</td>
<td>19.579 ± 0.005</td>
<td>-2.432 ± 0.013</td>
<td>715 ± 3</td>
<td>-13277 ± 171</td>
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</tr>
<tr>
<td>S3 (E)</td>
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<td>1101 ± 60</td>
<td>-13389 ± 8778</td>
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</tr>
<tr>
<td>U1</td>
<td>174.682492</td>
<td>-36.961938</td>
<td>13.701 ± 0.178</td>
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<td>6834 ± 1</td>
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</table>

*Origin is located at longitude 174.75°, latitude = −37°.
volume change $-13277$ and $-13389$ m$^3$/yr. Three regions of uplift were modeled by three point sources: uplift S1 was modeled as a point source located at depth 866 m with volume change 7930 m$^3$/yr; uplift S2 was modeled as a point source located at depth 902 m with volume change 4377 m$^3$/yr; and uplift U3 was modeled as a point source located at depth 926 m with volume change 6834 m$^3$/yr. A reasonable accuracy was achieved for sources S1, S3(West), and U3, while the accuracy for other sources was moderately lower (Table 2).

5. Discussion and Conclusions

[23] In this work we present ground deformation signals observed at the Auckland Volcanic Field, North Island of New Zealand during 2003–2007. This area is of great importance because of the coincidence of past volcanic activity and modern dense population of over one million in the city of Auckland. At the same time, analysis of past volcanic activity suggests that the magnitude of a new eruption when it occurs will be large.

[24] Over a hundred Envisat interferograms spanning 2003–2007 were calculated and advanced processing was performed. All three techniques (stacking, Small Baseline Subset and Permanent Scatterers) produced average deformation rates with corresponding errors and SBAS and PS techniques also produced time series; however, in this work only the SBAS time series are presented. The interpretation of the observed deformation rates suggests absence of a large deformation signal between 2003 and 2007, but a variety of deformation signals of small spatial extent and magnitude are observed. We concentrated our attention on three uplift regions (marked as U1, U2, and U3 in Figures 3a, 4a, and 6a) with approximate rates of 0.4 cm/yr and three subsidence regions (marked as S1, S2, and S3 in Figures 3a, 4a, and 6a) with approximate rates of $-0.4$ cm/yr. In order to determine origin of the observed signal we performed inversion of the ground deformation using a Mogi point source approximation. We determined location, depth, and volume change for each source, which are presented in Table 2. The depth of modeled sources lies between 451 m (S1) and 1101 m (U1). Cassidy et al. [1986] estimated that the source of basaltic magma lies at much greater depths of approximately 70–140 km and magma ascent during the observational period would have certainly produced localized seismicity. However, during the 2003–2007 period only a few small earthquakes (M < 3) were observed, and none of them were close to the observed deforming regions. Therefore, due to the lack of evidence for a volcanic or tectonic origin of these deformations it is proposed that they are produced by changes in near-surface groundwater levels: either through extraction or natural recharge.

[25] A geological map of the Auckland Volcanic Field is presented in Figure 9, and outlines of the observed signals

![Figure 9](image_url)
are plotted in blue (subsidence) and in red (uplift) based on visual analysis of Figure 3a. Locations of known groundwater wells are plotted as triangles for currently operational wells and smaller circles for wells that were active recently but presently abandoned. The groundwater well information for this region is very limited. However, based on the available information, we determined that the location of subsidence S1 precisely coincides with four wells that currently are used for supplying water to a food processing plant. These wells were drilled to a depth of 500 m (corresponding to the 451 m determined by our inversion) and have been operational since 2001. The maximum allowed extraction rate for each of these wells is 12000 m$^3$/yr. Our modeling suggests a volume change of $-4174$ m$^3$/yr, which means that groundwater recharge is not able to supply sufficient amounts of water, causing drops in groundwater levels and consequently ground subsidence. Another groundwater well precisely coincides with the location of subsidence S2. The depth of this well is not know (587 m according to our modeling) but the maximum allowed extraction rate is 304050 m$^3$/yr, which is well above the volume change provided by our modeling ($-3859$ m$^3$/yr). The larger subsidence S3 can be also explained since it coincides with at least fourteen currently active groundwater wells that have supplied water for agricultural irrigation purposes since the 1980s. It is clear that our modeling with two Mogi point sources located at 715 and 1101 m and producing a volume change $-13277$ and $-13389$ m$^3$/yr is only a first-degree approximation, which can be easily improved based on more precise locations of each groundwater well.

Further work is required in order to validate the use of a Mogi model, as well as our choice of elastic modulus; however, these results support the identification of the current deformation patterns in the AVF and the initial estimation of source parameters. In Figure 7 we plot the maximum vertical displacement that would be produced by a volcanic source (Mogi point source approximation) of various strengths and depths. Our work demonstrates that, assuming that the frequency of observations is sufficiently high, InSAR is capable of detecting the scale, rate, and magnitude of ground deformations that would likely accompany magma ascent into the crust, a process that could result in the resumption of volcanic activity beneath New Zealand’s largest urban area.

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