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.

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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

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Figure 1. Shaded relief DEM (in meters) of the Auckland Volcanic Field (inside rectangle) and outlines of observed ground deformation (uplifts U1–U3 and subsidence U1–U3). Known faults are plotted as black lines.

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 $\sim 100 \times 100$ 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,

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

Image	Time	Span
1	20030718	0
2	20030926	70
3	20031031	105
4	20031205	140
5	20040109	175
6	20040213	210
7	20040319	245
8	20040423	280
9	20040528	315
10	20040702	350
11	20040910	420
12	20041015	455
13	20041224	525
14	20050408	630
15	20050513	665
16	20050617	700
17	20050722	735
18	20050930	805
19	20051104	840
20	20051209	875
21	20060324	980
22	20060602	1050
23	20060811	1120
24	20060915	1155
25	20070309	1330
26	20071109	1575

^aThe image acquired on 20031205 had a large orbital error and was removed from further processing. Time is given in YYYYMMDD format.

2005; Houghton *et al.*, 2006], which, with a population of one million is New Zealand's largest urban area and is almost exactly coincident with the field.

[5] Basement faults form an orthogonal pattern, trending both northeast–southwest and northwest–southeast. Where volcanic vents cluster, they are sometimes aligned northeast–southwest, possibly reflecting a structural control. The thickness of the seismic crust beneath the AVF is estimated at approximately 25 ± 2 km [Stern *et al.*, 1987; Horspool *et al.*, 2006], while the brittle–ductile transition lies at ~ 15 –20 km [Sherburn *et al.*, 2007].

[6] The AVF is currently monitored by the Auckland Volcano–Seismic Network (AVSN), consisting of five telemetered, vertical-component, short-period (1 Hz) seismographs, four of which are situated in shallow (10–30 m) boreholes to reduce ambient noise, and four strong motion sensors. Data are digitized at 100 Hz and transmitted to GNS Science in Taupo and Wellington for near-real-time analysis [Sherburn *et al.*, 2007]. Based on seismic precursors to eruptions from historically active volcanic fields, instrumental detection of an impending eruption could occur between 9 and 14 days before surface activity as ascending magma interacts with the base of the crust to produce deep long period earthquakes, although events would need to be much shallower (~ 5 km) before their epicentral locations could be used to constrain a possible vent location [Sherburn *et al.*, 2007]. Ground deformation monitoring would be difficult to apply in the AVF because of its large areal extent, but dense kinematic GPS measurements could be made following the onset of seismicity [Miller *et al.*, 2001]. InSAR techniques are more promising because of their large areal coverage, while the abundance of paved surfaces in the city reduces decorrelation and maximizes coherence [Massonnet and

Feigl, 1998]. The difficulty with InSAR is the low frequency of observations, with a 35 day interval between Envisat overflights, however, it is expected that the revisit time will be significantly shortened in the future (e.g., satellite constellation). In this work we aim to evaluate the feasibility of InSAR for mapping ground deformation 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 [Wegmüller 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 $\times$ 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

Figure 2. Differential interferograms used in this study. In red and green (117) interferograms with $Bp < 400$ m that were used for stacking and SBAS processing. In green (78) interferograms with perpendicular baseline $Bp < 300$ m employed in PS processing only.

because of the simplicity of the matrix computation. The same 117 interferograms ($Bp < 400$ m) were used to create a set of 117 equations with 25 unknown velocities (v). The solution was calculated only for pixels that were coherent ($\gamma > 0.3$, where γ 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 2π 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.

Figure 3. (a) Stack with (b) corresponding errors calculated from 117 differential interferograms with $Bp < 400$ m acquired by Envisat satellite between 2003 and 2007. Stack was calculated only for pixels that were coherent on 110 out of 117 interferograms. Areas of subsidence (in blue) and uplift (in yellow-orange) are clearly visible. Earthquakes with maximum magnitude between 1.7 and 3.0, occurring between 1998 and the present are shown as black dots. There was no seismic activity observed on land during 2003–2008 in proximity to observed deformation regions.

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 north-west 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 dis-

tance 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

Figure 4. (a) Linear rates of deformation calculated from 117 differential interferograms with $Bp < 400$ m acquired by the Envisat satellite between 2003 and 2007 using Small Baseline Subset technique. The calculations were done only for pixels that were coherent on all 117 interferograms. DEM error correction was performed. (b) RMS error shows the deviation from a linear trend. Earthquakes with maximum magnitude between 1.7 and 3.0 occurring between 1998 and the present are shown as black dots.

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, 4, 8, 16, and 32 km plotted using a log-log scale in order to capture a large range of source strengths 10^3 – 10^9 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

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.

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:

$$u_r = \frac{3a^3 \Delta P}{4\mu} \frac{r}{R^3}, \quad u_z = \frac{3a^3 \Delta P}{4\mu} \frac{d}{R^3}, \quad (1)$$

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.

where u_r and u_z are the radial and vertical displacements, a is the source radius and ΔP is the pressure change, μ 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 $a^3 \Delta P$. Instead it was proposed to reformulate the Mogi model according to *Tiampo et al.*

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.

Figure 8. (a) Results of computer modeling and (b) residual signal of deformation rates obtained by stacking, using Mogi point source model and Simulating Annealing plus Simplex optimization algorithms. Earthquakes with maximum magnitude between 1.7 and 3.0 occurring between 1998 and the present are shown as black dots.

[2000] to relate the ground deformation to the source volume change:

$$u_r = \frac{3\Delta V}{4\pi} \frac{r}{R^3}, \quad u_z = \frac{3\Delta V}{4\pi} \frac{d}{R^3}, \quad (2)$$

where ΔV is the volume change.

4.1. Nonlinear Inversion Using the Derivative-Free Simplex Method

[21] 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 106 m^3 for the uplift signals and 0 to -106 m^3 for the subsidence signals.

[22] 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 model as a point source located at depth 587 m with volume change $-3858 \text{ m}^3/\text{yr}$; 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

Source	Longitude	Latitude	Easting ^a (km)	Northing ^a (km)	Depth (m)	Volume Change (m^3/yr)	RMSE (cm/yr)
S1	174.649955	-36.888961	-10.348 ± 0.001	12.313 ± 0.001	451 ± 1	-4174 ± 1	3.03
S2	174.825482	-36.934733	7.806 ± 0.199	7.237 ± 0.318	587 ± 144	-3859 ± 1029	3.03
S3 (W)	174.939379	-37.021722	19.579 ± 0.005	-2.432 ± 0.013	715 ± 3	-13277 ± 171	4.29
S3 (E)	174.914592	-37.033865	17.015 ± 0.064	-3.774 ± 0.028	1101 ± 60	-13389 ± 8778	4.29
U1	174.882492	-36.961938	13.701 ± 0.178	4.211 ± 0.013	866 ± 156	7930 ± 1376	4.32
U2	174.670118	-36.931915	-8.261 ± 0.057	7.549 ± 0.097	902 ± 26	4377 ± 78	2.48
U3	174.700367	-36.910937	-5.133 ± 0.001	9.879 ± 0.001	926 ± 1	6834 ± 1	3.09

^aOrigin is located at longitude 174.75°, latitude = -37° .

Figure 9. Geological map of Auckland Volcanic Field with locations of known groundwater wells. Regions of deformation are outlined in red (uplift) and blue (subsidence).

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

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 m³/yr. Our modeling suggests a volume change of −4174 m³/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 known (587 m according to our modeling) but the maximum allowed extraction rate is 304050 m³/yr, which is well above the volume change provided by our modeling (−3859 m³/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 volume change −13277 and −13389 m³/yr is only a first-degree approximation, which can be easily improved based on more precise locations of each groundwater well.

[26] Uplift U1, with a source at a depth 866 m and producing a volume change of 7930 m³/yr, according to our model, is probably caused by groundwater recharge, since at least 20 abandoned groundwater wells are located in close proximity to this region. The Mogi point source of the U1 uplift, however, cannot produce the elongated shape of the uplift in SW–NE direction. According to our investigations the uplift U2, whose modeled source is located at a depth of 902 m and producing a volume change of 4377 m³/yr likely is not groundwater related, as there are no (active or abandoned) groundwater wells located in that area. However, according to Figure 1, this region is overlain by steep topography. Therefore, residual topographic noise caused by inaccuracies in the DEM is the likely source of this artefact. The location of uplift U3, with a source at a depth of 926 m and a volume change of 6834 m³/yr, precisely coincides with the abandoned groundwater well with a depth 200 m active since 1996 (according to the records), and recently abandoned (exact date unknown). Its near circular shape and localized extent support this assumption.

[27] 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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