

# 50 years of steady ground deformation in the Altiplano-Puna region of southern Bolivia

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## ABSTRACT

The Altiplano-Puna Volcanic Complex of the Central Andes is host to an ~150-km-wide, quasi-circular ground deformation anomaly centered on Uturuncu volcano (Bolivia). The precise onset and duration of this deformation is unclear, but geomorphologic studies bracket its initiation at less than a few hundred years ago. Here we report on the deformation history over an ~50 yr period by deriving orthometric height changes from leveling and global navigation satellite system (GNSS) observations at 53 benchmarks along a regional leveling line that crosses the deformation anomaly. The comparison of interferometric synthetic aperture radar (InSAR) line-of-sight (LOS) displacements and LOS-projected orthometric ground velocities in a common reference frame reveal central uplift extending to ~35 km from Uturuncu at a maximum orthometric rate of 1.2 cm yr<sup>-1</sup>, and peripheral subsidence at a maximum rate of 0.3 cm yr<sup>-1</sup> to ~60 km from Uturuncu. This pattern is consistent with the spatial extent and average rate of deformation observed by InSAR. Our interpretation of the data is that long-wavelength ground uplift at Uturuncu has likely occurred at a quasi-constant rate for at least half of a century. This study bridges the observational time spans between modern satellite geodetic observations (up to a few decades) and geomorphological observations (a few centuries and longer) of the recent deformation history of the continental crust in the Central Andes and adds to a select group of case studies of quantifiable long-term volcano deformation worldwide.

## INTRODUCTION

Satellite remote sensing techniques documented an unusually wide and spatially complex ground deformation in the Altiplano-Puna Volcanic Complex (de Silva, 1989) between A.D. 1992 and 2011 (e.g., Pritchard and Simons, 2002; Henderson and Pritchard, 2013; Fialko and Pearse, 2012) (Fig. 1), with a diameter of 150 km, a peripheral moat of subsidence, and a central area undergoing uplift at rate of up to 1 cm yr<sup>-1</sup> at the western slopes of Uturuncu volcano (Bolivia; 22.270°S, 67.180°W) as detected in interferometric synthetic aperture radar (InSAR) line-of-sight (LOS) displacement data. The spatially and temporally complex deformation may be linked with an ~200-km-wide

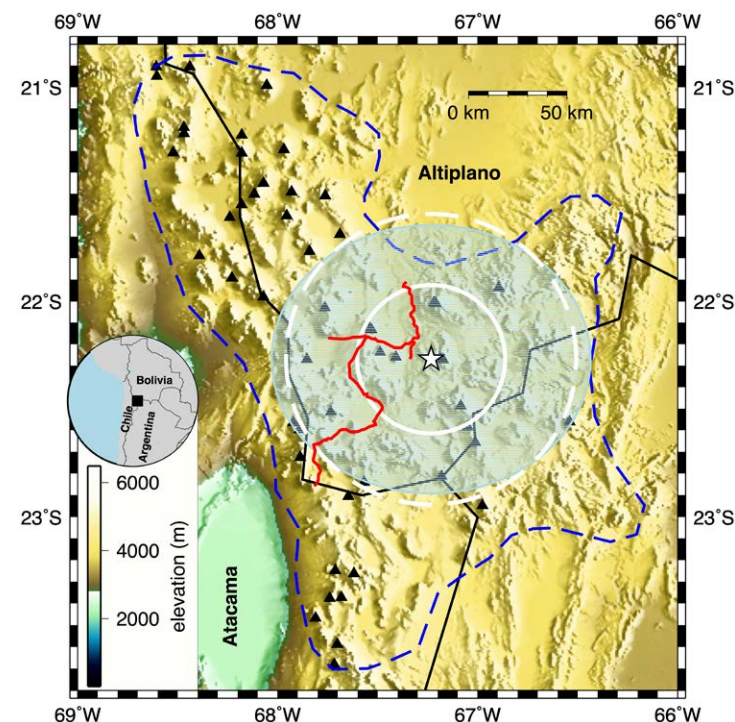


Figure 1. Overview map of the Altiplano-Puna region of southern Bolivia. White star (22.270°S, 67.233°W) marks the maximum uplift of ~1 cm/yr<sup>-1</sup> as detected by interferometric synthetic aperture radar (InSAR) line-of-sight measurements (Henderson and Pritchard, 2017), located on the western slope of Uturuncu volcano. Spatial extent of the uplifting region, determined to have a radius of ~40 km from InSAR data, is marked by a white solid circle. Peripheral subsidence, between ~40 and ~70 km distance, is shown by the white dashed circle. Dashed blue line outlines the spatial extent of the Altiplano-Puna Volcanic Complex (de Silva, 1989). The spatial extent of the 2.5 km s<sup>-1</sup> velocity contour of the S-wave velocity model of the Altiplano-Puna magma body at 20 km below sea level presented by Ward et al. (2014) is shown by the light-green transparent ellipse and is similar in size to the footprint of the InSAR anomaly. Black solid lines mark international borders; black triangles mark volcanic centers of the Altiplano-Puna Volcanic Complex. Red line shows the original leveling line (line BP), established in 1965. Elevations in the digital elevation model are given in meters above sea level.



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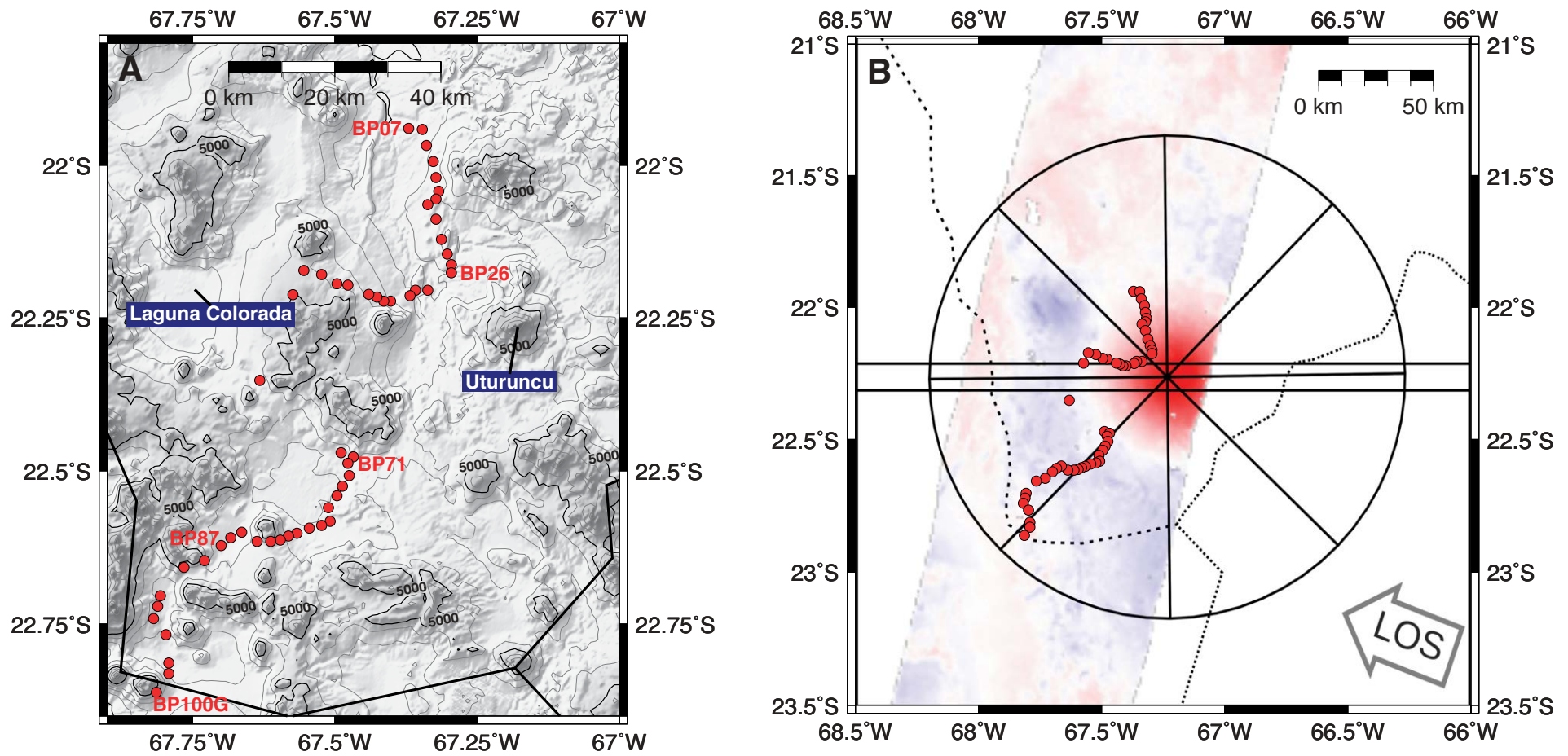


Figure 2. (A) Map showing benchmark locations along the main BP leveling line measured in this study, Altiplano-Puna region, southern Bolivia. Labeled contours indicate elevation in meters above sea level. (B) Location of the BP line within the quasi-axisymmetric interferometric synthetic aperture radar (InSAR) deformation anomaly recorded between 1992 and 2011; Henderson and Pritchard, 2017). Hot colors indicate uplift with maximum magnitude of  $1 \text{ cm yr}^{-1}$ ; cold colors represent subsidence at maximum magnitude of  $0.2 \text{ cm yr}^{-1}$ . Lines intersecting at the center of the anomaly show the location of profiles used to depict average interferometric synthetic aperture radar (InSAR) line-of-sight (LOS) ground velocity data shown in Figure 8. Horizontal black lines show the location of the east-west swath profile used to determine vertical and radial components of InSAR-detected deformation shown in Figure 7. Dotted lines mark international borders.

TABLE 1. BENCHMARK LOCATIONS ALONG LEVELING LINE BP, ALTIPLANO-PUNA REGION, SOUTHERN BOLIVIA

BM ID	Longitude (°W)	Latitude (°S)	Dist. BP (km)	Dist. InSAR (km)	<i>h</i> (m)
BP07	67.3704	21.9394	12.4	42.52	4081.60
BP08	67.3462	21.9415	14.54	41.02	4124.93
BP10	67.3389	21.9678	18.73	38.16	4117.65
BP12	67.3268	21.9941	22.79	33.88	4170.54
BP14	67.322	22.0204	26.54	31.82	4236.09
BP15	67.3172	22.0424	28.75	29.93	4287.22
BP16	67.322	22.0555	30.93	28.83	4263.41
BP17	67.3365	22.0643	32.87	28.49	4271.42
BP19	67.322	22.0884	36.72	25.39	4313.84
BP21	67.3123	22.1213	40.93	22.03	4394.58
BP23	67.3026	22.1454	44.57	19.27	4351.23
BP24	67.2954	22.1629	46.73	17.77	4284.53
BP26	67.2954	22.1761	49.57	16.54	4190.62
BP31	67.3365	22.2047	57.6	18.65	4275.09
BP32	67.3583	22.2047	59.63	20.45	4252.06
BP33	67.368	22.2135	61.27	21.18	4306.82
BP35	67.4019	22.2224	64.91	23.97	4477.89
BP36	67.414	22.2224	66.46	25.3	4562.37
BP37	67.4261	22.2159	68.1	26.67	4610.14
BP38	67.4406	22.2115	69.87	28.26	4656.12
BP40	67.477	22.1962	73.71	31.92	4733.04
BP41	67.4963	22.1941	75.67	33.47	4771.37
BP43	67.523	22.1788	79.44	36.55	4837.38
BP45	67.5544	22.1723	82.59	39.6	4878.89
BP48	67.5738	22.2118	88.14	40.7	4996.06
BP57	67.6319	22.3523	105.18	46.96	4750.22
BP69A	67.4891	22.4704	132.31	39.76	4476.26
BP69B	67.4673	22.4769	134.01	38.91	4481.88
BP71	67.477	22.4879	134.71	40.1	4458.20

continued

TABLE 1. BENCHMARK LOCATIONS ALONG LEVELING LINE BP, ALTIPLANO-PUNA REGION, SOUTHERN BOLIVIA (continued)

BM ID	Longitude (°W)	Latitude (°S)	Dist. BP (km)	Dist. InSAR (km)	<i>h</i> (m)
BP72	67.4745	22.5076	137.12	41.39	4451.47
BP73	67.4866	22.5252	139.16	43.32	4441.17
BP74	67.4963	22.5406	141.29	45.4	4443.38
BP75	67.5109	22.5604	143.35	47.18	4452.10
BP77	67.5084	22.5823	147.17	49.28	4449.43
BP78	67.523	22.5889	149.13	51	4450.26
BP79	67.5448	22.5933	151.22	52.99	4466.02
BP80	67.5665	22.6022	153.25	54.89	4525.97
BP81	67.5811	22.6066	155	56.46	4619.80
BP82	67.5956	22.6132	156.68	57.94	4721.98
BP83	67.6125	22.6154	158.55	59.39	4775.99
BP84	67.6368	22.6155	160.43	60.62	4756.39
BP86	67.6634	22.6002	164.02	62.17	4553.86
BP87	67.6828	22.609	166.1	64.06	4499.84
BP88	67.6997	22.6222	168.19	66.07	4531.68
BP90	67.7288	22.6464	172.35	69.98	4593.28
BP92	67.7651	22.6574	176.25	73.48	4772.22
BP96	67.8063	22.7036	184.4	80.5	4506.96
BP97	67.8111	22.7211	186.56	81.88	4471.60
BP98	67.8184	22.7409	188.74	83.49	4432.43
BP100	67.7966	22.7671	193.13	84.06	4382.41
BP100C	67.7917	22.8132	198.98	87.06	4375.32
BP100D	67.7917	22.8307	201.28	88.74	4438.15
BP100G	67.8135	22.8615	204.74	93.05	4520.73

Note: BM ID—benchmark identifier; Dist. BP—distance along main leveling line; Dist. InSAR—distance along an east-to-west radial profile from the center of deformation detected in interferometric synthetic aperture radar (InSAR) data; *h*—ellipsoidal heights of benchmarks along line BP shown in Fig. 2A.

To set an absolute reference for the gravity measurements, we chose an arbitrary benchmark (BP15) where gravity was measured during the survey, and used the gravity value on the geoid using model EGM2008 ( $g_{BP15} = 9.7887 \text{ m s}^{-2}$ ) to calculate the absolute gravity on the benchmark ( $g_{BP15}$ ) using the simplified Poincaré-Prey reduction (Hofmann-Wellenhof and Moritz, 2005) for an average crustal density of  $2670 \text{ kg m}^{-3}$ :

$$g_{BP15} = g_{0BP15} + 0.848 \times 10^{-6} \times H_{BP15}, \quad (1)$$

where  $H_{BP15}$  is the orthometric height of BP15 (see below for calculation of orthometric heights). We use the so-derived value  $g_{BP15} = 9.7923 \text{ m s}^{-2}$  as a reference for all relative gravity values measured in the survey. This procedure does not affect the gravity change values along the leveling line relative to BP15. See Table 2 for a list of notations used in this study.

### Conversion to Orthometric Heights

GNSS data cannot be directly compared with leveled heights. The former provide Cartesian (XYZ) solutions that do not express a notion of elevation above a certain datum, whereas the latter depend on the geopotential surface along the path followed (Fig. 3). To permit direct comparison, both data sets must be converted to orthometric heights.

First, GNSS solutions are transformed into geodetic latitude, longitude, and ellipsoidal heights using the WGS84 ellipsoid model (Hofmann-Wellenhof and Moritz, 2005). Ellipsoidal heights (*h*) are then converted to (approximate) orthometric heights (*H*) by means of the geoid undulation (*N*; Figs. 3 and 4) (Hofmann-Wellenhof and Moritz, 2005) using:

$$H = h - N. \quad (2)$$

TABLE 2. SYMBOLS AND NOTATIONS USED IN THIS STUDY

Notation or symbol	Description	Value or units
$\gamma_0$	Theoretical value of gravity at 22°S	m s <sup>-2</sup>
$g$	Gravity at observation point	m s <sup>-2</sup>
$\Delta g$	Measured difference in gravity between two benchmarks	mGal
$g_{oBP15}$	Theoretical gravity on geoid at benchmark BP15 used as absolute reference (see Equation 1 in text)	9.7887 m s <sup>-2</sup>
$h'$	Leveled height of benchmark	m
$\Delta h'$	Leveled height difference between two benchmarks	m
$h$	Ellipsoidal height of benchmark	m
$H$	Orthometric height of benchmark	m
$N$	Geoid undulation (see Fig. 4 in text)	m
OC	Orthometric correction (see Equation 3 in text)	m
$k$	Vertical offset between $LOS_{\Delta H}$ and $LOS_{InSAR}$	m
$LOS_{InSAR}$	Deformation observed in interferometric synthetic aperture radar (InSAR) line-of-sight (LOS) data	m
$LOS_{\Delta H}$	Orthometric height change of benchmark projected onto the InSAR LOS	m

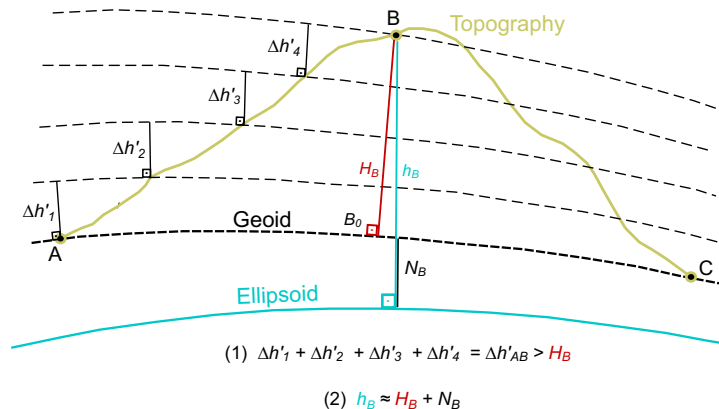


Figure 3. Schematic diagram illustrating reconciliation of leveled, orthometric, and ellipsoidal heights between two benchmarks, A and B, along geopotential surfaces (black stippled lines). Leveling increments ( $\Delta h'$ ) from level measurements at a set of intermediate points are summed to determine the difference in leveled height ( $\Delta h'_{AB}$ ) and are converted to orthometric height differences ( $\Delta H_{AB}$ ) by adding an orthometric correction (see Equation 3 and text). In the example, geoid undulation  $N_B$  is subtracted from ellipsoidal heights  $h_B$  determined from global navigation satellite system (GNSS) measurements to obtain orthometric height  $H_B$  (cf. Equation 2).

For this we have used the national geoid model BOLGEO (Corchete et al., 2006) (Fig. 4 and the Supplemental File [footnote 1]), which provides better accuracy compared to a global model such as EGM2008. EGM2008 and BOLGEO can be reconciled by adding a vertical offset of 2.2 m to EGM2008.

Because of the nonparallelism of geopotential (level) surfaces, elevations of benchmarks from spirit leveling are not only different from heights above the

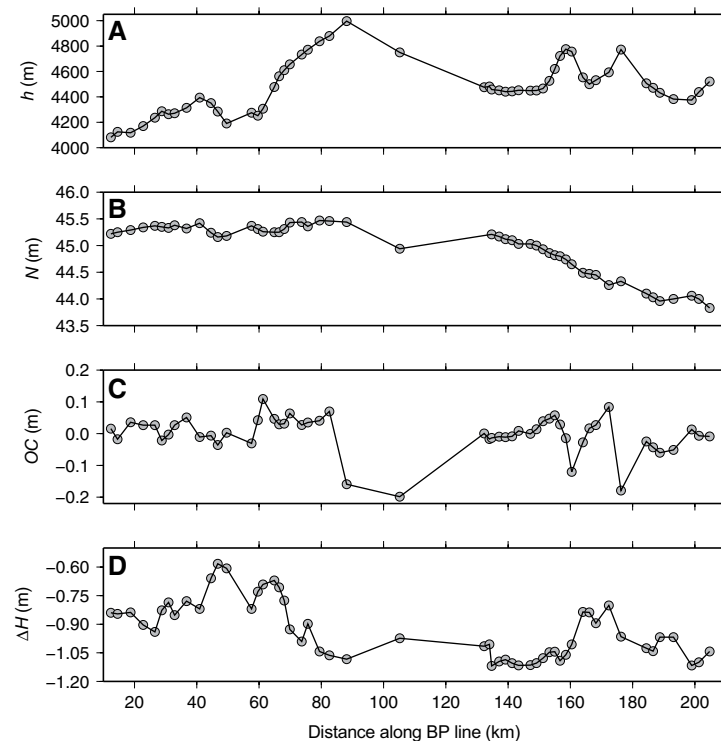


Figure 4. Geodetic parameters as a function of distance along leveling line BP running north-south (see Fig. 2) and derived orthometric height changes, Altiplano-Puna region, southern Bolivia. (A) Ellipsoidal heights of benchmarks. (B) Undulations ( $N$ ) of geoid model BOLGEO (Corchete et al., 2006). (C) Orthometric correction (OC) applied to each benchmark according to Equation 3. (D) Derived orthometric height changes ( $\Delta H$ ) between 1965 and 2012.

geoid (such as orthometric heights) but also ambiguous; i.e., they are path dependent (Hofmann-Wellen Hof and Moritz, 2005). Level heights ( $h'$ ) must hence be converted to orthometric heights ( $H$ ) (see Fig. 3). This is done by adding an orthometric correction (OC) to  $h'$ . Because we do not know the datum for the leveled heights, orthometric corrections are given relative to the previous point measured along the line. The correction between two benchmarks on the Earth's surface, A and B, is given by (Hofmann-Wellen Hof and Moritz, 2005):

$$OC_{AB} = \sum_A^B \frac{g - \gamma_0}{\gamma_0} \Delta h' + \frac{\bar{g}_A - \gamma_0}{\gamma_0} h'_A - \frac{\bar{g}_B - \gamma_0}{\gamma_0} h'_B, \quad (3)$$

where  $\gamma_0$  is the theoretical (normal) gravity calculated for 22.26°S latitude (9.784 m s<sup>-2</sup>),  $g$  is the gravity determined at the level points between A and B, and  $\Delta h'$  is the leveling increment.  $h'_A$  and  $h'_B$  are the leveled heights of points A and B respectively (see Supplemental File [footnote 1]).  $\bar{g}_A$  and  $\bar{g}_B$  are the mean val-

ues of gravity along the plumb lines between the geoid and benchmarks A and B and are calculated as the arithmetic mean of  $g$  at the level points and their respective gravity on the geoid  $g_o$  (using a simplified Poincaré-Prey reduction) (Hofmann-Wellenhof and Moritz, 2005):

$$\bar{g} = 1/2 (g + g_o), \tag{4}$$

$$\bar{g} = g + 0.424 \times 10^{-6} \cdot h'. \tag{5}$$

Because in most cases there were no gravity measurements taken between BP benchmarks, the summation of  $g$  was simplified to the average of gravity measured at two consecutive benchmarks.

### RESULTS

The two sets of orthometric heights, derived from leveling and GNSS observations, are compatible and thus comparable (see Supplemental File [footnote 1]). Derived orthometric height changes between 1965 and 2012 along the main leveling line vary between  $-0.60$  m and  $-1.15$  m and are shown in Figure 4D. The constant offset is a combination of datum offsets, the choice of reference gravity, and the vertical movement of the entire region between 1965 and 2012. This implies a maximum relative height change along the leveling line of 0.55 m between the two surveys. We can derive the spatial deformation pattern from the orthometric height differences over 47 yr by plotting the differences along a radial westward trajectory from the center of the InSAR anomaly (Fig. 5).

The orthometric height change pattern shows relative uplift of up to 45 cm in the area of ground inflation detected by InSAR to a radial distance of  $\sim 40$  km. From there, up to 15 cm of subsidence are observed over 20 km, which coincides with an area where InSAR data show the start of an  $\sim 20$ -km-wide area of LOS subsidence. The resultant orthometric deformation pattern is hence similar to the spatial deformation pattern derived from 18 yr of InSAR observations in terms of relative magnitude, wavelength, and position of areas of uplift and subsidence.

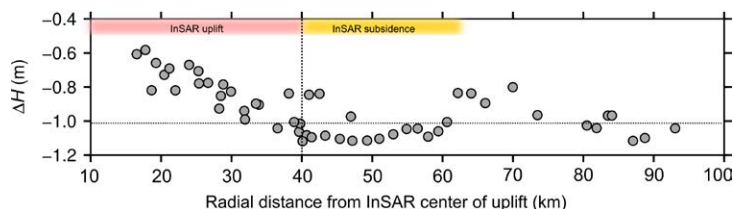


Figure 5. Orthometric height changes ( $\Delta H$ ) between 1965 and 2012 as a function of radial distance from the center of the deformation anomaly observed in interferometric synthetic aperture radar (InSAR) data. Areas of uplift and subsidence as detected by InSAR are shown for reference. Horizontal stippled line marks a tentative line of zero net deformation based on InSAR observations. Note that the  $\Delta H$  data have not been georeferenced for direct comparison with InSAR-detected deformation. See text for details.

### DISCUSSION

The absence of a common datum for the InSAR and orthometric deformation data introduces an unknown vertical offset between them. To address this, one possible solution is to assume that a given point has not moved at all, whereby  $\Delta H = 0$ ; one then uses that point as an arbitrary anchor between the two surveys. A different approach, followed here, is to use the known deformation trend from 18 yr of InSAR observations as a calibration to test whether the deformation patterns are indeed comparable and can be used to inform the deformation history since 1965. This calibration, however, has to be done with care, as both orthometric height change and InSAR LOS displacement are one-dimensional measurements of the true three-dimensional (3-D) displacement (Fig. 6). Changes in orthometric height ( $\Delta H$ ) represent the vertical component ( $u_z$ ) of the true three-component displacement vector, while InSAR LOS displacement data give the projection of the true displacement vector onto the satellite LOS.

#### Comparison of Orthometric Height Changes to InSAR-Observed Deformation

As shown in Figure 6, given a true displacement vector  $v_A$  of benchmark  $BP_A$ , composed of both upward ( $u_z$ ) and westward ( $u_r$ ) components (whereby  $u_z = u_r$  in the case shown), the change in orthometric height ( $\Delta H_A$ ) does not equal the change in InSAR LOS ( $LOS_{InSAR A}$ ). This is also true if  $\Delta H_A$  is projected

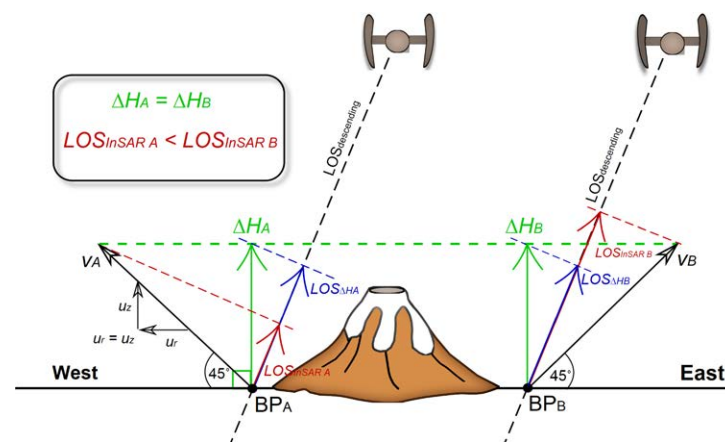


Figure 6. Schematic diagram of the interpretation of differences between displacements detected in descending interferometric synthetic aperture radar (InSAR) line-of-sight (LOS) data ( $LOS_{descending}$ ) and orthometric height changes ( $\Delta H_A$  and  $\Delta H_B$ ) determined from leveling and GNSS data for eastward and westward displacements of virtual benchmarks  $BP_A$  and  $BP_B$ . While the magnitudes of eastward and westward displacements at  $BP_A$  and  $BP_B$  ( $v_A$  and  $v_B$ ) are equal, the magnitudes of resultant InSAR LOS displacements ( $LOS_{InSAR A}$  and  $LOS_{InSAR B}$ ) are different. The illustration depicts the case of equal radial ( $u_r$ ) and vertical ( $u_z$ ) displacements of  $BP_A$  and  $BP_B$ . Figure is not to scale.

onto the InSAR LOS ( $LOS_{\Delta HA}$ ). The mismatch between the orthometric deformation and InSAR-observed deformation becomes smaller for deformation dominated by vertical movement, but larger where horizontal deformation dominates. Moreover, two different 3-D displacement vectors,  $v_A$  and  $v_B$  measured at  $BP_A$  and  $BP_B$ , respectively, can yield the same magnitude of orthometric deformation  $\Delta H_{A,B}$  if projected onto the InSAR LOS ( $LOS_{\Delta HA,B}$ ) despite drastically different magnitudes of InSAR LOS displacement. This is due to the direction of the horizontal deformation component relative to the satellite's LOS with an incidence angle of  $22^\circ$  for the available descending InSAR tracks (Henderson and Pritchard, 2017).

### Projecting Orthometric Displacements onto InSAR LOS

The BP benchmarks located within the uplifting part of the InSAR anomaly (BP12 to BP37) are located northwest of Uturuncu. Assuming that the horizontal component of the deformation is radially away from Uturuncu, the east-west component of the deformation for a descending radar track that illuminates the area from the east would contribute to the lengthening of the radar path and yield a smaller magnitude in the InSAR LOS displacement compared with the magnitude of the projected orthometric height change ( $LOS_{\Delta H}$ ) (see Fig. 6).

We use the orthometric vertical displacements for each benchmark to project them into the InSAR LOS and derive a set of synthetic  $LOS_{\Delta H}$  displacements that would arise from a perfectly radially symmetric uplift pattern such as one caused, e.g., by a buried pressurized sphere. Then we use the available InSAR LOS displacements data to help determine the magnitude of the vertical offset  $k$  in the orthometric height changes ( $\Delta H$ ) if projected onto the InSAR LOS, whereby:

$$k = LOS_{InSAR} - w \times LOS_{\Delta H} \tag{6}$$

in order to obtain LOS displacements in a common reference frame. Note that the magnitude of  $LOS_{\Delta H}$  is modulated by parameter  $w$  whose value is dependent on the magnitude of radial displacement ( $u_r$ ) relative to the magnitude of vertical displacement ( $u_z$ ) at the leveling benchmarks. For example, for  $u_r/u_z = 0$  (i.e., only vertical displacement and no radial displacement),  $w = 1$  and  $k = LOS_{InSAR} - LOS_{\Delta H}$ . For  $u_r/u_z = 1$  (i.e.,  $u_r = u_z$ ),  $w = 0.4$  and  $k = LOS_{InSAR} - 0.4 \times LOS_{\Delta H}$ .

In the above analysis, we limit the parameter space exploration of  $u_r/u_z$  to values up to 1, because a strong horizontal component acting radially from the center of the deformation would cause a horizontally elongated InSAR deformation pattern. This is inconsistent with the large-scale concentric InSAR pattern observed to date (e.g., Henderson and Pritchard, 2017).

### Derivation of Deformation Velocities between 1965 and 2012

Using  $u_r$  and  $u_z$  data from an inversion of four overlapping InSAR tracks (Henderson and Pritchard, 2017), we find that  $u_r/u_z$  ratios are between  $-0.05$  and  $0.25$  over a distance of  $\sim 60$  km from the center of the InSAR uplift (Fig. 7A). According to Figure 7B,  $w$  hence takes values between 0.9 and 1.

The resultant vertical offset  $k$  from Equation 6 obtained by a residual minimization procedure is  $2.0 \pm 0.05$  cm  $yr^{-1}$ , or  $94 \pm 2.4$  cm over 47 yr. Note, that this extrapolation assumes a constant linear evolution of the deformation between 1965 and 2012.

Adding the offset to the above LOS-projected orthometric height differences, we derive the spatial ground velocity pattern shown in Figure 8. This pattern is remarkably similar to the spatial deformation pattern from 18 yr of InSAR observations in terms of magnitudes and wavelengths of both inflation and subsidence. This implies that the uplift rate recorded along the leveling line running north-south toward Uturuncu (benchmarks BP12 to BP26) is equal

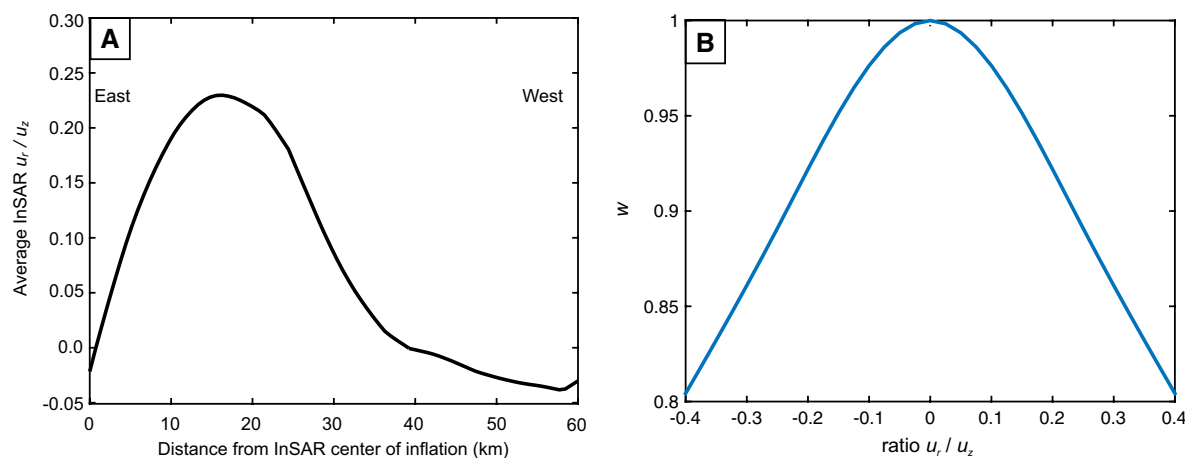
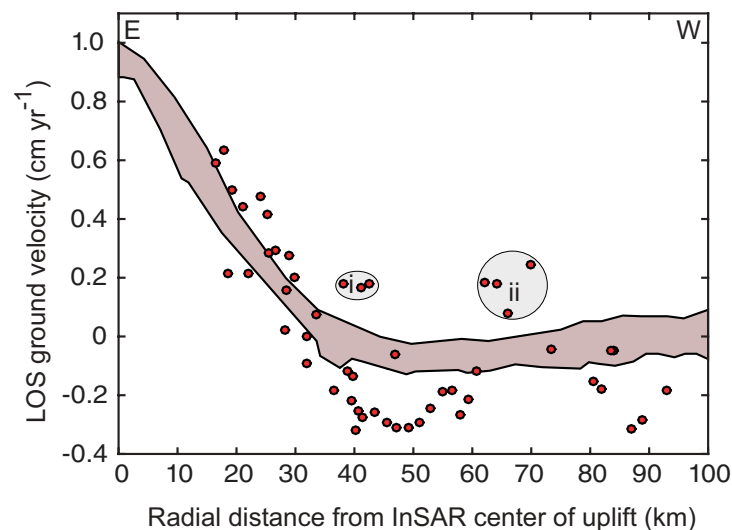


Figure 7. (A) Ratios of radial to vertical displacements  $u_r/u_z$  as a function of distance from the center of uplift derived from interferometric synthetic aperture radar (InSAR) deformation data presented by Henderson and Pritchard (2017). (B) Parameter  $w$  as a function of selected  $u_r/u_z$  ratios to convert the magnitudes of the projected orthometric height changes ( $LOS_{\Delta H}$ ) data for the ratios shown in A according to Equation 6.



**Figure 8.** Comparison of line-of-sight (LOS) ground velocities from interferometric synthetic aperture radar (InSAR) (brown shading encompasses data from profiles shown in Fig. 2; data from Henderson and Pritchard, 2017) and orthometric measurements (red dots) along a radial trajectory from the center of maximum InSAR deformation westwards, Altiplano-Puna region, southern Bolivia. Orthometric height changes have been projected onto the InSAR LOS data, shifted by best-fit offset  $k$  (see Equation 6) and linearly averaged over a 47 yr observation period. The orthometric subsidence velocities have a higher magnitude than those detected by InSAR, which is likely due to an observation bias of InSAR data for subsidence west of Uturuncu volcano for descending radar tracks. The orthometric data identify anomalous uplift at the start of the leveling line to the northwest of Uturuncu (i) and near the active volcanic chain close to the Chilean border (ii).

to that recorded along the east-west segment (BP32 to BP45), suggesting that the vertical deformation is indeed radially symmetric from Uturuncu. A deformation source that causes a radially symmetric deformation pattern can hence reasonably explain the observations.

Extrapolating the  $LOS_{\Delta H}$  ground velocities to the center of the uplift observed by InSAR and accounting for uncertainties in the derivation of velocities, we propose a maximum velocity  $LOS_{\Delta H}$  of  $1.1 \pm 0.2 \text{ cm yr}^{-1}$ . These values are within the uncertainty of maximum InSAR LOS ground velocities of  $1.05 \pm 0.07 \text{ cm yr}^{-1}$ . The orthometric uplift extends  $\sim 35 \text{ km}$  from Uturuncu, and peripheral subsidence, at a maximum rate of  $\sim 0.3 \pm 0.03 \text{ cm yr}^{-1}$ , extends to  $\sim 60 \text{ km}$  from Uturuncu. The fact that the leveling line crosses the moat of subsidence to the west of the center of deformation, where InSAR observations are less reliable to detect the true magnitude of ground deflation, allows us to confirm that subsidence has indeed occurred albeit at slightly higher mean velocities than inferred from InSAR measurements.

The consistency of the spatial pattern and ground velocities between the orthometric and InSAR deformation data indicates that the long-wavelength deformation may have been constant for at least 47 yr (1965–2012). This al-

lows us to suggest a near-constant deformation of the Altiplano-Puna Volcanic Complex over decadal time scales under the assumption that this is not a coincidence of the discrete sampling in time (1965, 1992, 2010–2011) of an oscillatory inflation-deflation process. Deriving mean velocities over such time scales from only two surveys is inherently problematic. Currently, we have no means to test our hypothesis due to the absence (to the best of our knowledge) of additional geodetic data over the same period. However, continuous GNSS observations near the center of uplift observed by InSAR indicate that the recent rate of uplift dropped to an average of  $0.24 \pm 0.19 \text{ cm yr}^{-1}$  between 2010 and 2016 (Blewitt et al., 2016), similar to the long-term average detected above the Socorro magma body (Finnegan and Pritchard, 2009). Whether this uplift will continue to decelerate or accelerate again in the future remains to be seen. Either behavior has implications for the assessment of causative processes behind the complex spatio-temporal deformation. Their discussion is beyond the scope of this paper, and we refer interested readers to Gottsmann et al. (2017) where some of the implications of nonlinear history of the deformation anomaly are considered.

## CONCLUSIONS

Leveling and GNSS data collected in 1965 and 2012, respectively, have allowed us to convert deformation data into orthometric height changes along a leveling line that crosses the 150-km-wide deformation anomaly centered on Uturuncu. Due to the absence of a common geodetic datum for the orthometric and InSAR displacement data, the two data sets cannot be directly compared. However, we obtain a reasonable match between the two data sets by projecting the orthometric height changes into the InSAR LOS and applying a vertical offset of  $94.0 \pm 2.4 \text{ cm}$  over the 47 yr to the orthometric height changes. The ground deformation velocity pattern from 1965 to 2012 is equivalent to that observed by InSAR surveys between 1992 and 2011. We therefore propose a near-constant long-term pattern of ground deformation between 1965 and 2012 with central maximum orthometric uplift at  $1.2 \pm 0.2 \text{ cm yr}^{-1}$  and maximum peripheral subsidence at  $0.3 \pm 0.03 \text{ cm yr}^{-1}$  over the 150-km-wide deformation anomaly. This study adds to a select group of long-term geodetic investigations that quantitatively document protracted periods of complex spatio-temporal deformation in volcanic terrain (e.g., Finnegan and Pritchard, 2009; Parker et al., 2014). Exploitation of these data should improve our understanding of the link between protracted crustal stress changes and decadal time scales of magma transfer and reservoir growth (e.g., Druitt et al., 2012).

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