An extraordinary episode of Yellowstone caldera uplift, 2004–2010, from GPS and InSAR observations

Wu-Lung Chang,[1] Robert B. Smith,[2] Jamie Farrell,[2] and Christine M. Puskas[2]

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[1] Geodetic measurements of Yellowstone ground deformation from 2006 to June 2010 reveal deceleration of the recent uplift of the Yellowstone caldera following an unprecedented period of uplift that began in 2004. In 2006–2008 uplift rates decreased from 7 to 5 cm/yr and 4 to 2 cm/yr in the northern and southwest caldera, respectively, and in 2009 rates further reduced to 2 cm/yr and 0.5 cm/yr in the same areas. Elastic-dislocation modeling of the deformation data robustly indicates an expanding sill at ~7–10 km depth near the top of a seismically imaged, crystallizing magma reservoir, with a 60% decrease in the volumetric expansion rate between 2006 and 2009. Reduction of hydrothermal-volcanic recharge from beneath the northeast caldera and seismic moment release of the 2008 and 2010 large earthquake swarms are plausible mechanisms for decelerating the caldera uplift and may have influenced the change in recent caldera motion from uplift to subsidence. **Citation:** Chang, W.-L., R. B. Smith, J. Farrell, and C. M. Puskas (2010), An extraordinary episode of Yellowstone caldera uplift, 2004–2010, from GPS and InSAR observations, *Geophys. Res. Lett.*, *37*, L23302, doi:10.1029/2010GL045451.

1. Introduction

[2] The late-Quaternary Yellowstone silicic volcanic system is characterized by extensive earthquake activity, extraordinarily high heat flow, widespread hydrothermal activity, and rapid variations of ground deformation [e.g., *Smith et al.*, 2009]. Geodetic techniques including precise leveling, GPS (Global Positioning System), and InSAR (Interferometric Synthetic Aperture Radar) revealed multiple episodes of Yellowstone caldera uplift and subsidence from 1923 to 2003 with average rates of 1–2 cm/yr [*Wicks et al.*, 2006; *Puskas et al.*, 2007; *Chang et al.*, 2007]. In addition, a secondary zone of uplift across the northern caldera rim near Norris Geyser Basin was observed from 1987 to 2003 by GPS and InSAR measurements, with an average rate of 1.0 ± 0.5 cm/yr [*Wicks et al.*, 2006]. Spatial and temporal variations of Yellowstone ground movement are correlated with changes in seismic and hydrothermal activity in and around the caldera [*Waite and Smith*, 2002, *Chang et al.*, 2007, *Smith et al.*, 2009].

[3] To monitor the temporal variation of ground deformation in the context of the evolution of Yellowstone's volcanic features and related hazards, the University of Utah and EarthScope PBO (Plate Boundary Observatory) deployed and operated 14 continuous-recording GPS stations within Yellowstone National Park (Figure 1a). In mid-2004, GPS data revealed an acceleration of ground uplift across the entire caldera, while subsidence near the northern caldera boundary initiated about two months later [*Chang et al.*, 2007]. The GPS and InSAR measurements indicated unexpectedly high uplift rates up to 7 cm/yr through 2006, over three times faster than that of previous caldera inflation episodes. Concurrently, the subsidence rate of −3.5 cm/yr in the northern caldera was more than two times greater than that recorded in 1996–2003.

[4] In this paper we present new measurements of Yellowstone deformation through mid-2010 and evaluate the temporal variations of magmatic sources interpreted to be responsible for this most recent episode of caldera unrest. These results together with an analysis of seismic activity of the Yellowstone caldera provide information on how decadal-scale uplift episodes are considered in the context of volcano hazards.

2. GPS and InSAR Measurements

[5] Position time series of continuous GPS stations (for more information see the auxiliary material) in and around the Yellowstone caldera consistently reveal a reduction in uplift rates from 2006 to 2010 (Figure 2) compared to the accelerated uplift from 2004 to 2006.[1] The maximum total uplift of ~25 cm was recorded at station WLWY, located on the Sour Creek resurgent dome in the northeast caldera, where the average uplift rate has decreased from ~7 ± 0.2 cm/yr before 2007 to 5 ± 0.3 cm/yr and 2 ± 0.3 cm/yr in the periods of 2007–2008 and 2008–2009, respectively (Figure 1b). At the Mallard Lake resurgent dome in the southwest caldera, vertical motion at station OFW2 near Old Faithful has decreased from 4.2 ± 0.2 cm/yr to 2.3 ± 0.2 cm/yr in 2008 and 0.5 ± 0.2 cm/yr in 2009 (Figure 1b). The Norris area has experienced ground subsidence with rates from −3.2 ± 0.2 cm/yr in 2004–2006 to −0.9 ± 0.2 cm/yr in 2008–2009 at station NRWY.

[6] Note that Figure 2 reveals a caldera-wide change to subsidence along with coincident changes in horizontal motions (e.g., from SE to NW at WLWY) during the first six months of 2010. Although further geodetic observations are needed to confirm the continuation of the subsidence to avoid disturbances of non-tectonic transient signals, the association of this deformation with the 2010 earthquake swarm (Figure 2) is notable and will be discussed later in this paper.

[1]Department of Earth Sciences, National Central University, Jhongli, Taiwan.
[2]Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, USA.

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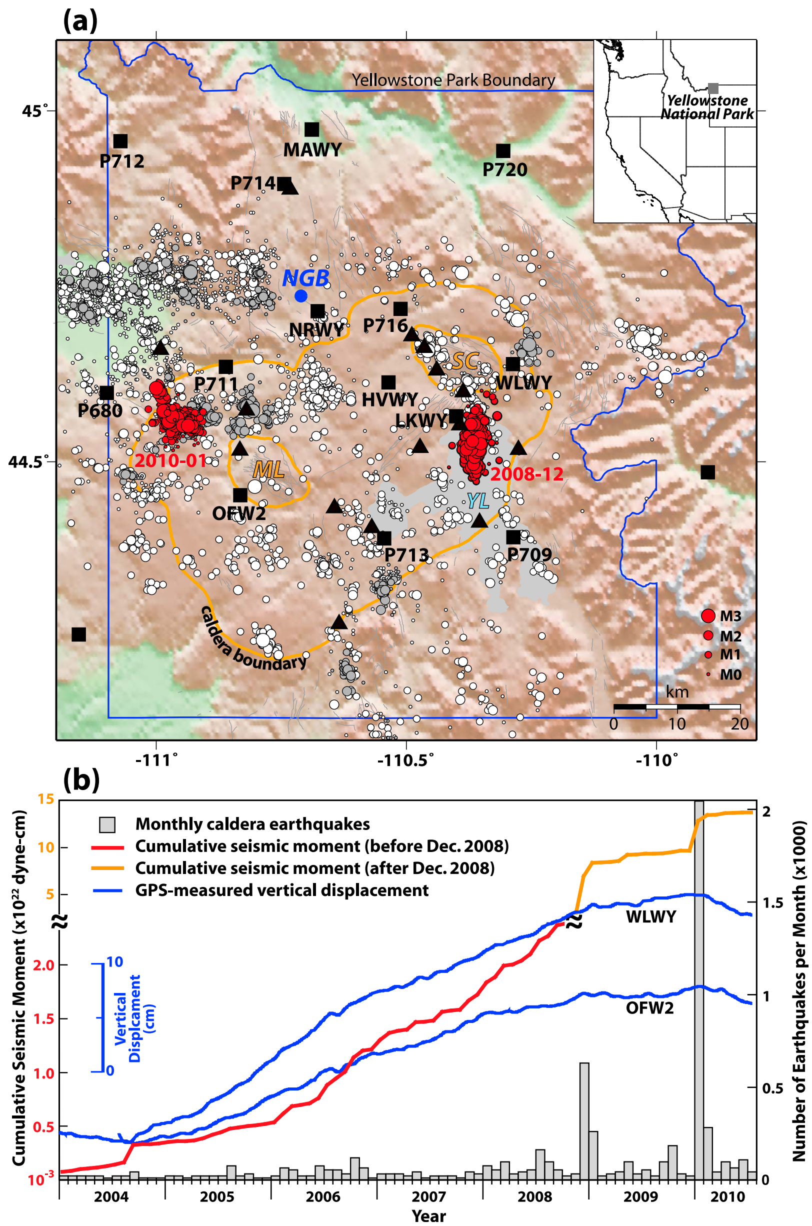

Figure 1. (a) Map showing the Yellowstone volcanic system and locations of continuous (squares) and campaign (triangles) GPS stations used in this study. SC, Sour Creek dome; ML, Mallard Lake dome; NGB, Norris Geyser Basin, YL, Yellowstone Lake. White and gray circles show background seismicity and swarm earthquakes during the period of the 2004–2010 caldera uplift, respectively. The two large earthquake swarms at the north of Yellowstone Lake (2008–12) and the western caldera boundary (2010–01) are shown in red circles. Gray lines show Quaternary faults. (b) Monthly earthquakes and the cumulative seismic moment within the caldera, together with vertical displacements of the GPS stations WLWY and OFW2.

[7] Responding to this unprecedented deformation episode, the University of Utah conducted two GPS surveys in Yellowstone during the summers of 2008 and 2009, reoccupying 15 sites established in earlier surveys near the two resurgent domes where the highest rates of caldera inflation were observed (Figure 1a). Data from these surveys supplemented the permanent GPS stations to increase the spatial sampling of ground deformation (Figure 3). These data reveal up to 2.5 cm of uplift and 0.8 cm of horizontal motion radially outward from the Sour Creek dome in 2008–2009. The caldera uplift was lower to the southwest (~0.5–0.6 cm), and reversed to subsidence toward the northwest caldera boundary. Note that the previous GPS survey in Yellowstone was conducted in 2003, prior to the start of this deformation episode. For comparison, we estimated the ground motion based on the 2003 and 2008 survey data. The results show a similar deformation pattern but much higher rates than that of 2008–2009 GPS observations.

[8] InSAR measurements of the Yellowstone area also show spatial and temporal variations of ground deformation in a near-vertical, or satellite line-of-sight (LOS), direction from the autumn periods of 2004 to 2009. Figure 3 shows that the recent 2008–2009 caldera uplift had magnitudes of ~2 cm at the Sour Creek dome and <1 cm at the Mallard Lake

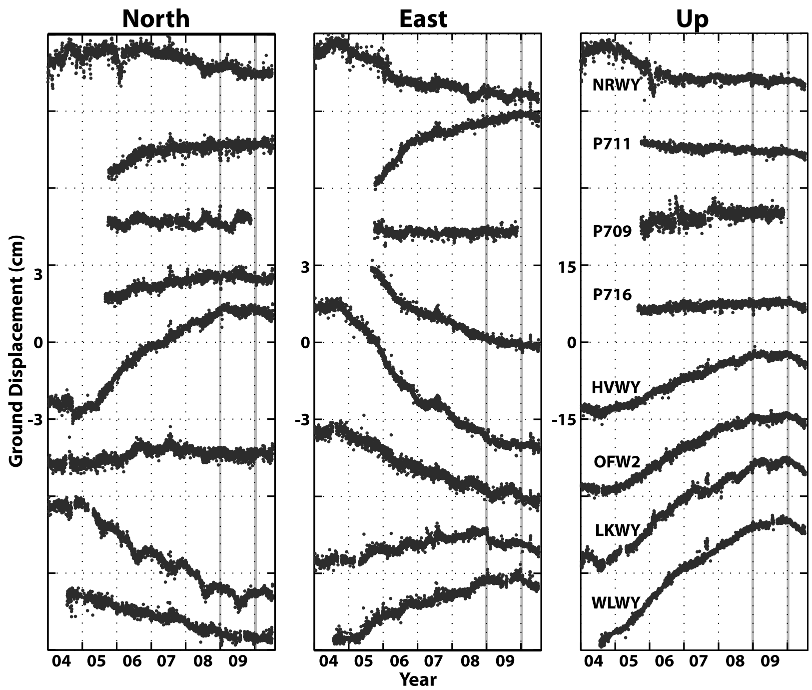

Figure 2. Temporal variations of Yellowstone caldera ground deformation determined by GPS. Each dot represents a daily position coordinate. From left to right the upward trend denotes north, east, and up motions, respectively, with up components scaled five times larger than the north and east. Gray lines indicate the time of the Dec. 2008 and Jan. 2010 earthquake swarms.

dome. An area of subsidence is also revealed across the northern caldera boundary near Norris, similar to that given by *Chang et al.* [2007] although the maximum LOS velocity decreased from −3.5 cm/yr in 2004–2006 to −1 cm/yr in 2009.

3. Source Modeling

[9] We employed a nonlinear optimization technique [*Cervelli et al.*, 2001; *Chang et al.*, 2007] to evaluate the geometry and volume change of rectangular dislocation sources in a homogeneous elastic half-space that best fit the GPS and InSAR measurements for three distinct time periods: 2005–2007, 2007–2008, and 2008–2009. The map and oblique views of the best-fitting source models are shown in Figure 4, which include inflating sills with optimal dips of <6° and depths of 7–9 km beneath the caldera (Table S3). These modeled sills also have a geometry and location comparable to the inverted source for the 2004–2006 accelerated uplift [*Chang et al.*, 2007], with the area reduced about 30% in 2009. We therefore suggest the same expanding source was responsible for the caldera uplift since 2004.

[10] The average rate of volumetric expansion of the caldera source decreased from 0.11 km^3/yr in 2004–2006 [*Chang et al.*, 2007] to 0.06–0.07 km^3/yr and 0.03 km^3/yr in 2005–2008 and 2008–2009, respectively. Note that previous caldera deformation episodes were consistent with source volume changes of 0.01–0.03 km^3/yr [*Wicks et al.*, 1998; *Vasco et al.*, 2007] that are 2–10 times lower than our modeled rates of 2004–2008 but comparable to the value of 2008–2009.

[11] The modeled deflating sources were located at 7–13 km depth beneath the Norris area with rates of volumetric contraction decreasing from −0.02 to −0.004 km^3/yr in 2005–2009 (Figure 4). The confidence ranges of the source depths (Table S3) suggest the same contracting volume during the time period, with its location similar to an

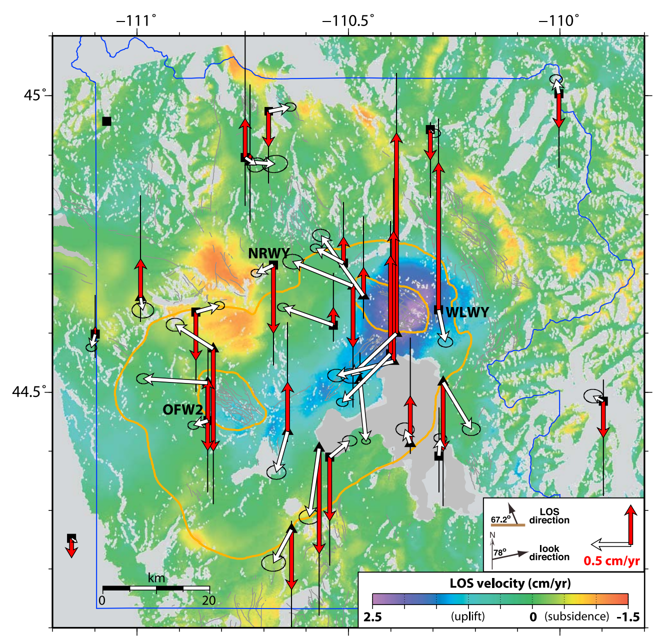

Figure 3. 2008–2009 Yellowstone ground motion determined by InSAR (LOS velocity in background) and GPS (red and white arrows denote vertical and horizontal velocities, respectively) observations. Squares and triangles represent permanent and campaign GPS stations, respectively. Two ENVISAT IS2 images of 08/27/2008 and 09/16/2009 were used to form the interferogram. Ellipses and bars represent 2-σ errors.

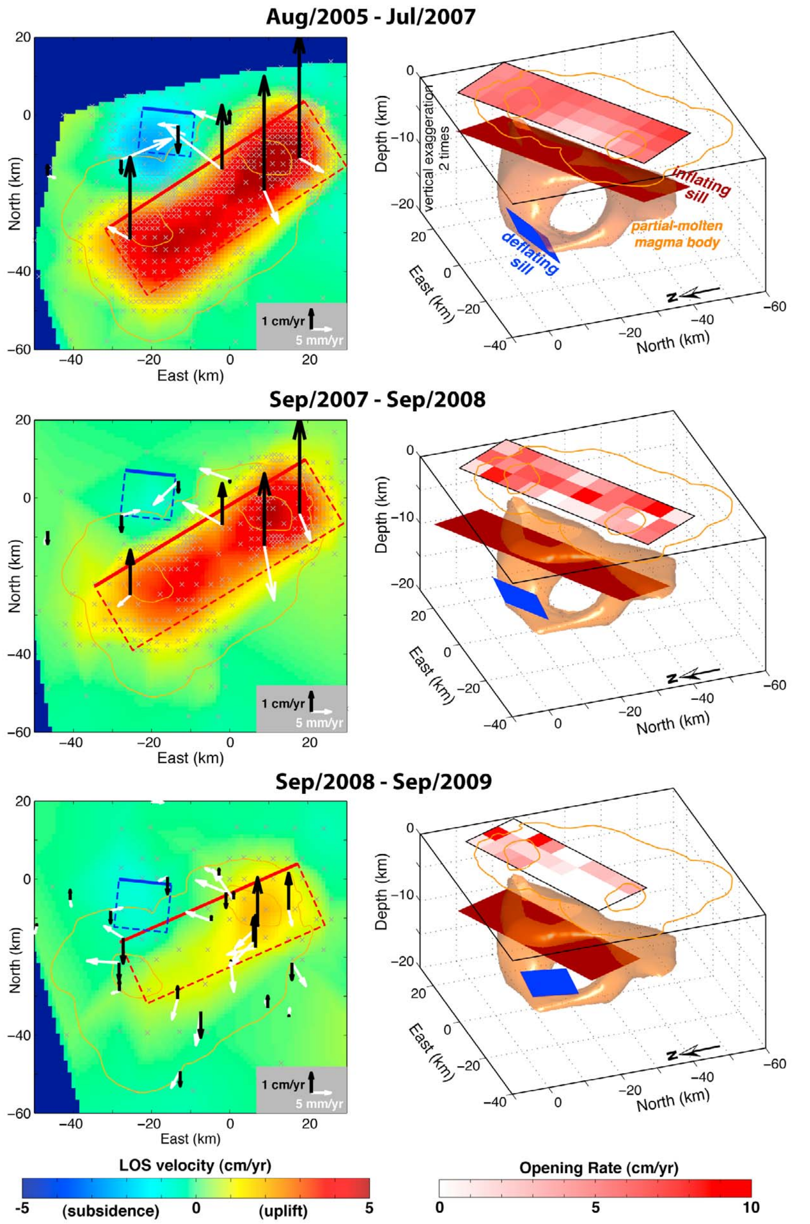

Figure 4. Source models of the Yellowstone crustal motion for three periods from 2005 to 2009. (left) Observed horizontal (white arrows) and vertical (black arrows) GPS velocities with background colors showing LOS velocity field measured by InSAR. Gray crosses are InSAR data points used for source inversion. Red and blue dashed rectangles represent surface projections of modeled inflating and deflating sources, with solid lines indicating the up-dip edges of the dislocations. (right) Oblique view (from NW) of the modeled sills superimposed on a seismically imaged partial-molten body (see text). The distribution of opening rates of the inflating sill is shown on the top. The vertical exaggeration is a factor of two.

expanded magmatic sill modeled for InSAR measurements of the ground uplift in 1996–2001 [*Wicks et al.*, 2006].

4. Discussion

[12] Figure 4 shows that the modeled caldera sills of the 2005–2009 geodetic data are near the top of a seismically imaged crystallizing magma reservoir at ~8 km beneath the surface [*Husen et al.*, 2004]. This scenario is similar to that of the 2004–2006 source model [*Chang et al.*, 2007], suggesting that the pressurization of the Yellowstone crustal magmatic system, possibly due to migration of magmatic fluids from deeper (>10 km) to shallower parts of the magma reservoir [*Fournier*, 1989], can be the mechanism of the caldera uplift through 2009.

[13] While magmatic intrusion was proposed as a plausible mechanism for the 2004–2009 Yellowstone uplift, circulation of shallow hydrothermal fluids (water and gases) could induce poroelastic transients and in turn cause rapid ground inflation and deflation [e.g., *Battaglia et al.*, 2006; *Hutnak et al.*, 2009]. Seismic and geochemical evidence suggested that the brittle, permeable hydrothermal system of the Yellowstone caldera is shallower than ~5 km [*Fournier*, 1989; *Dzurisin et al.*, 1994], while our modeled

caldera sill was shown to be deeper (7–10 km) and therefore would preferably be a magmatic source. Note that the sill could be even deeper if realistic mechanical models such as layered or anisotropic medium were considered [*Manconi et al.*, 2007; *Masterlark*, 2007]. Moreover, the source modeling of the 1992–1995 caldera subsidence and 1995–1997 uplift episodes also indicated volume changes at 6–10 km depth [*Wicks et al.*, 1998; *Vasco et al.*, 2007], and the lack of hydrothermal anomalies observed in Yellowstone during 2004–2009 is more compatible with magmatic sources for deformation [*Ingebritsen et al.*, 2001]. Based on these discussions we suggest magmatic intrusions to be the main source of the current caldera uplift episode.

[14] Viscoelasticity of caldera host rocks surrounding magma chambers could also cause the ground uplift to decelerate. *Newman et al.* [2006] proposed that rocks surrounding magmatic sources are heated and weakened beyond the brittle-ductile transition temperature and therefore become viscoelastic, which can cause the temporal variation of surface deformation being exponential instead of a linear pattern implied by pure elasticity. Their numerical results successfully explained most time-dependent ground deformation data of the Long Valley caldera, California, from 1995 to 2000, which included an episode of accelerated then decelerated inflation similar to the 2004–2009 Yellowstone uplift (Figure 2). Modeling this effect would require further observations to evaluate recoverable and permanent ground displacements related to a viscoelastic process.

[15] The higher uplift rates in the northeast caldera relative to the southwest and the lateral decrease of sill expansion from northeast to southwest (Figure 4) could be caused by spatial variations of magma intrusion. *DeNosaquo et al.* [2009] modeled the largest negative Bouguer gravity anomaly of Yellowstone, −80 Mgal north of the Sour Creek dome, and suggested that the anomaly source was an active crustal magma reservoir extending ~10 km northeast of the caldera. This anomaly was inferred as fertile magma that is replenished from Yellowstone's mantle plume [*Smith et al.*, 2009]. Therefore, the inflation would be expected the greatest in the northeast caldera as magmatic replenishment continues from below, consistent with the pattern that the Sour Creek dome has the highest vertical motion during the caldera uplift. This mechanism may also explain the northeast to southwest migration of the Yellowstone caldera uplift from 1995 to 1997 [*Wicks et al.*, 1998].

[16] Rapid changes in vertical ground motion accompanied by elevated seismicity have been previously observed in Yellowstone [*Waite and Smith*, 2002]. Figure 1b shows that the caldera seismic moment rate was the lowest, $\sim 2 \times 10^{21}$ dyne-cm/yr, during the accelerated uplift in 2005 and then increased by a factor of 2 to 3 in 2006–2008 as the uplift decelerated. From December 2008 to January 2009, one of the two largest earthquake swarms during the current inflation episode occurred at the northern edge of Yellowstone Lake with a total moment release of 6×10^{22} dyne-cm [*Farrell et al.*, 2010], ~3 times larger than the total caldera seismic moment since 2004. Following this swarm the caldera vertical motion experienced an additional decrease in 2009 as described earlier in this paper.

[17] Here we propose that as the caldera source continues inflating, the accumulated strain energy in the deformed crust could promote earthquakes with mechanisms such as hydrofracturing [*Taira et al.*, 2010], migration of magmatic fluids [*Farrell et al.*, 2010], and brittle fracturing of rocks. These events can subsequently depressurize the magmatic systems or release the accumulated strain energy, slowing the uplift or even influencing a change in motion to subsidence. In January 2010 the Yellowstone caldera experienced another large earthquake swarm at its northwestern boundary close to the location of the 1985 swarm, with a total moment of $\sim 3 \times 10^{22}$ dyne-cm (Figure 1). In the following five months the caldera experienced the first overall subsidence since the inception of its uplift in 2004 (Figures 1b and 2). This scenario is similar to that in 1985 where a reverse of caldera uplift to subsidence was temporally correlated with the largest observed Yellowstone earthquake swarm [*Waite and Smith*, 2002]. While the continuation of the subsidence requires further examination, this observation provides new evidence for the correlation between transient ground deformation and changes in seismic activity of the Yellowstone region.

5. Concluding Remarks

[18] GPS and InSAR measurements reveal that Yellowstone caldera uplift rates have decreased by a factor of 3–4 from 2006 to 2009 following a period of accelerated uplift. Based on source modeling results, we interpret that magmatic intrusions at 7–10 km beneath the caldera have been responsible for the uplift since mid-2004. A decreasing rate of magmatic replenishment from beneath the northeast caldera and an increase of seismic moment release are interpreted as plausible mechanisms for the continuing but declining caldera uplift. GPS data, to June 2010, reveal the beginning of a caldera-wide subsidence following the January 2010 Yellowstone earthquake swarm, but additional observations are needed to confirm the independence of this deformation from non-tectonic transient signals.

[19] Observations of cyclical Yellowstone crustal deformation are key to evaluating the hazards of this active volcanic system. Such data as documented in this paper improve understanding of the relation between time-dependent deformation and magma migration, and help differentiate between hydrothermal and magmatic sources.

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W.-L. Chang, Department of Earth Sciences, National Central University, 300 Jhongda Rd., Jhongli 32001, Taiwan. (wuchang@ncu.edu.tw)

J. Farrell, C. M. Puskas, and R. B. Smith, Department of Geology and Geophysics, University of Utah, 135 S. 1460 E, Salt Lake City, UT 84112, USA.