Renewed Uplift at the Yellowstone Caldera Measured by Leveling Surveys and Satellite Radar Interferometry

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Abstract

A first-order leveling survey across the northeast part of the Yellowstone caldera in September 1998 showed that the central caldera floor near Le Hardy Rapids rose 24 ± 5 mm relative to the caldera rim at Lake Butte since the previous survey in September 1995. Annual surveys along the same traverse from 1985 to 1995 tracked progressive subsidence near Le Hardy Rapids at an average rate of -19 ± 1 mm/yr. Earlier, less frequent surveys measured net uplift in the same area during 1923-76 (14 ± 1 mm/yr) and 1976-84 (22 ± 1 mm/yr). The resumption of uplift following a decade of subsidence was first detected by satellite synthetic aperture radar interferometry, which revealed about 15 mm of uplift in the vicinity of Le Hardy Rapids from July 1995 to June 1997. Radar interferograms show that the center of subsidence shifted from the Sour Creek resurgent dome in the northeast part of the caldera during August 1992-June 1993 to the Mallard Lake resurgent dome in the southwest part during June 1993-August 1995. Uplift began at the Sour Creek dome during August 1995-September 1996 and spread to the Mallard Lake dome by June 1997. The rapidity of these changes and the spatial pattern of surface deformation suggest that ground movements are caused at least in part by accumulation and migration of fluids in two sill-like bodies at 5-10 km depth, near the interface between Yellowstone's magmatic and deep hydrothermal systems.

Key Words: Yellowstone, caldera, leveling, radar interferometry, uplift, subsidence, volcano

Background

The 0.63 Ma Yellowstone caldera has hosted numerous earthquakes, vigorous hydrothermal activity, and rapid crustal deformation throughout the twentieth century. Similar activity has evidently occurred for thousands of years. Tilted terraces and other geomorphic indicators of surface deformation record several cycles of decameter-scale uplift and subsidence within the caldera during postglacial time (Pierce et al. 1996).

The first geodetic detection of crustal motion at Yellowstone resulted from a comparison of leveling surveys conducted in 1923 and 1975-77, which revealed that the central part of the caldera floor rose at an average rate of 14 ± 1 mm/yr (Pelton and Smith 1979, 1982; Fig. 1). Less extensive, annual surveys starting in 1983 showed additional uplift from 1976 to 1984 (22 ± 1 mm/yr) followed by progressive subsidence from 1985 to 1995 at an average rate of -19 ± 1 mm/yr (Dzurisin and Yamashita 1987; Dzurisin et al. 1990, 1994). This paper compares leveling and satellite radar interferometry results for the period 1992-98, including the most recent leveling survey in September 1998.

Satellite Radar Interferometry Results

Against the backdrop of persistent and rapid deformation revealed by repeated leveling surveys, Wicks et al. (1998) conducted a study of contemporary crustal motion at Yellowstone using satellite interferometric synthetic aperture radar (InSAR). InSAR is a relatively new remote sensing technique that, under favorable conditions, can be used to map millimeter- to centimeter-scale ground movements over large areas (typically 100 km x 100 km) at a spatial resolution of approximately 10 m (Massonnet 1997). For specific information on how the Yellowstone interferograms were formed and analyzed, see Wicks et al. (1998). Here we describe the main features of four of the interferograms for comparison with leveling results for the period 1992-98.

Wicks et al. (1998) used radar images from the European Space Agency’s ERS-1 and

ERS-2 satellites to form several interferograms of the Yellowstone region for the 1992-97 time period. Four of these are shown in Fig. 2. Those for August 1992-June 1993 and June 1993-August 1995 (A and B) show subsidence of the caldera floor by amounts that generally agree with leveling for similar time periods (all leveling surveys since 1984 were conducted in September). For the period 1992-93, leveling measured -13 ± 5 mm of subsidence near Le Hardy Rapids relative to Lake Butte (Dzurisin et al. 1994), compared to approximately -20 mm indicated by the corresponding interferogram. For 1993-95, leveling measured -39 ± 5 mm compared to about -40 mm deduced from InSAR. The leveling and InSAR results for 1992-97 are compared in Fig. 4 of Wicks et al. (1998) and Fig. 3 of this paper. The accuracy of both techniques is discussed below.

A surprising discovery from the InSAR study is that the center of subsidence shifted from the northeast half of the Yellowstone caldera during 1992-93 to the southwest half during 1993-95 (i.e., from the vicinity of the Sour Creek resurgent dome to the Mallard Lake dome; see Fig. 2A, B). None of the earlier leveling surveys had detected any movement of the deformation center, in hindsight because they were either too infrequent (complete surveys in 1923, 1975-77, 1987) or too limited in extent (partial, annual surveys from 1983 to 1995; see Fig. 1).

An interferogram for August 1995-September 1996 contained an even bigger surprise. It showed that, while the Mallard Lake dome continued to subside slightly, the Sour Creek dome started to rise—apparently for the first time since 1984 (Fig. 2C). The interferogram shows ~20 mm of uplift centered a few kilometers east of the leveling traverse. By June 1997, uplift extended across most of the caldera, and its center had risen ~40 mm since August 1995 (Fig. 2D). This finding was confirmed by the September 1998 leveling survey, which showed 24 ± 5 mm of uplift near Le Hardy Rapids relative to Lake Butte since September 1995 (see

Discussion).

Accuracy of InSAR Results

The accuracy of InSAR results is a complex function of many factors including radar design, viewing geometry, atmospheric and ionospheric conditions, surface properties, and data processing. The C-band radars aboard the ERS satellites operate at a half-wavelength of 28 mm, so accuracy of a few millimeters is theoretically possible from interferometric analysis of ERS images. This level of accuracy has been realized in several cases with favorable circumstances, but several factors can degrade the quality of interferograms and thus reduce the accuracy of ground displacements inferred from them. A key factor in determining the quality of an interferogram is coherence—the degree to which scattering elements on the surface at the scale of the radar wavelength and larger maintain their radar-reflective properties from one image to the next. With strong coherence, interferometric fringes are easy to recognize. Poor coherence produces faint fringes or none at all. The accuracy of a displacement measured by a single picture element of an interferogram is essentially meaningless, because the ability to measure ground movements with InSAR depends less on the dispersion of random elements than it does on the recognition of fringes. Thus, in practical terms, calculating the formal uncertainty of displacements derived from interferograms is difficult. An empirical approach is better. For example, an estimate of the uncertainty can be made by comparing independent interferograms formed from different pairs of images, or by subtracting a best-fit model to produce a residual interferogram.

By varying the size of a cell over which picture elements were averaged, Wicks et al. (1998) showed that displacements deduced from the Yellowstone interferograms were generally consistent within a few millimeters. An exception occurred along a 10 km segment at the south end of the leveling traverse, where the 1995-97 interferogram is relatively noisy and the results of averaging over various cell sizes did not converge to a consistent estimate of ground displacement (see Fig. 4C of Wicks et al. 1998). Wicks et al. (1998) also produced a residual interferogram for the period 1993-95, which showed that the misfit between data and model was small compared to the half-wavelength of the ERS radars (28 mm).

In general, the Yellowstone InSAR results are probably accurate to ± 5 mm over distances of a few tens of kilometers. Over longer distances, residual uncertainty in the satellite orbits gives rise to orbital fringes that were removed from the Yellowstone interferograms by subtracting a uniform tilt. This procedure likewise removes any real tilt that might exist across the entire interferogram, so comparison of the InSAR results with leveling or GPS data over large distances is not meaningful. This may be pertinent to the 1995-98 results for Yellowstone, as discussed below.

Leveling Procedures and Accuracy

The 1998 leveling survey, like all USGS surveys at Yellowstone since 1975, was conducted in accordance with standards for first-order, class II surveys established by the Federal Geodetic Control Committee (1974, 1975). All appropriate corrections recommended by the Committee, including those for rod scale and refraction, were applied to the Yellowstone data. Equipment used for the 1998 survey included a Wild NA2 level (S/N 459655), Leica NA3003 digital level (S/N 93884), Wild rods 6815A & 6571A, and Leica rods 27599 & 27451.

Specific procedures and accuracy for the 1975-95 surveys at Yellowstone were discussed previously (Pelton and Smith 1979, 1982; Dzurisin and Yamashita 1987; Dzurisin et al. 1990, 1994). For the most part, the same discussion applies to the 1998 survey. The standard deviation of a vertical displacement measured by modern first-order, class II surveys is given by:

$_h \quad 1\frac{mm}{\sqrt{km}} \sqrt{L}$ (Vanicek et al. 1980). For the Yellowstone traverse between Lake Butte and Mount Washburn, this means that $_h$ is approximately 5 mm at the center of the traverse (benchmark DA 3 near Le Hardy Rapids, L = 23.4 km) and 7 mm at the north end (R 366 on Mount Washburn, L = 49.4 km), both with respect to 36 MDC near Lake Butte. These statistics describe only random errors that remain after appropriate corrections have been applied to the data. They do not account for uncorrected systematic error, which can be reduced by field procedures outlined by the Committee and followed for the 1975-98 surveys.

From 1984 to 1988, annual surveys were conducted between 36 MDC near Lake Butte and 11 MDC at Canyon Junction. From 1989 to 1998, the surveys were extended about 5 km farther north to R 366 at Mount Washburn.

Leveling Results, 1995-98

Vertical displacements along the Lake Butte-Mount Washburn traverse derived from comparison of the September 1995 and September 1998 leveling surveys are shown in Fig. 3. A displacement profile derived from the InSAR results for July 1995-June 1997 along the same traverse is also shown for comparison. Leveling showed that benchmark DA 3 near Le Hardy Rapids rose with respect to 36 MDC near Lake Butte, which was held fixed for the comparison, by 24 ± 5 mm from 1995 to 1998. This agrees reasonably well with the InSAR result for 1995-97 (15 mm). On the other hand, leveling suggests that benchmark R 366 at the north end of the traverse moved up 30 ± 7 mm during 1995-98, while the InSAR profile shows that any movement at the north end of the traverse during 1995-97 was negligible. This comparison is clouded by the fact that orbital fringes were removed from the interferogram before the InSAR profile was calculated. This process removes a uniform tilt, so that information about any real ground tilt across the entire interferogram is lost.

Uplift at Mount Washburn by 30 ± 7 mm relative to Lake Butte during 1995-98 is unusual. All of the earlier surveys along this traverse show that maximum displacement (uplift or subsidence) occurs near Le Hardy Rapids (DA 3), and any movement at the north end of the traverse is relatively small (Fig. 4). There is some tendency for Canyon Junction to move up or down together with Le Hardy Rapids, especially during 1976-86 and 1990-98, but the relationship is not convincing and might simply be the result of leveling error (Fig. 5). For example. relatively large movements apparently occurred at Canyon Junction during 1985-86 (-19 ± 7 mm), at the onset of subsidence, and again during 1995-98 (30 ± 7 mm), when uplift resumed. On the other hand, Canyon Junction apparently moved up 22 ± 7 mm with respect to Lake Butte during 1987-88, then down -26 ± 7 mm during 1988-89, while Le Hardy Rapids was subsiding at a nearly constant rate of -10 ± 5 mm/yr.

Any tendency for Canyon Junction to move in the same direction as Le Hardy Rapids when uplift changes to subsidence or vice versa would be intriguing, but we can offer no plausible explanation for the observations other than leveling error. Most models for deformation at Yellowstone invoke processes occurring beneath the caldera and do not account for cross-caldera tilt. For example, Dzurisin et al. (1990) proposed that uplift-subsidence cycles at Yellowstone are caused by magmatic inflation-deflation or hydrothermal pressurization-depressurization. Tectonic strain is another possibility, but Savage et al. (1993) showed that the horizontal strain pattern from 1973 to 1987 was consistent with a zone of rifting that extends from the adjacent Hebgen Lake area southeastward across the caldera to the Sour Creek dome. The hypothesized rifting axis crosses the Lake Butte-Mount Washburn leveling traverse obliquely about 10 km north of Le Hardy Rapids. Extension across this axis would not produce the sort of cross-caldera tilt seen in Fig. 3. Therefore, the most plausible explanation for the apparent movement at Canyon Junction relative to Lake Butte during 1985-86 and 1995-98 is uncorrected leveling error.

Uplift of the caldera floor during 1995-98 stands in clear contrast to the pattern of progressive subsidence during 1984-95. Whereas DA 3 near Le Hardy Rapids subsided at an average rate of -19 ± 1 mm/yr during 1984-95, it rose 8 ± 1 mm/yr during 1995-98. The timing of the change from subsidence to uplift is not well established by leveling, because there were no surveys in 1996 or 1997. However, the InSAR study by Wicks et al. (1998) shows that uplift resumed sometime between August 1995 and September 1996.

This period immediately follows the occurrence of an intense swarm of over 560 locatable earthquakes (largest M ~3.1) that began in late June 1995 and continued through mid-July 1995 (RB Smith and SJ Nava, written communication, 1996). The swarm was located just west of Madison Junction and occurred along the caldera’s northwest boundary. This was the second-most intense swarm of earthquakes ever recorded within the Yellowstone region. An even stronger swarm (largest M ~4.9, with 28 > M 3.5) in the same area started in October 1985 and persisted through 1986 (RB Smith, written communication, 1987). In that swarm, the earthquakes coincided with the beginning of subsidence that was detected by leveling surveys in September 1985 and September 1986.

Discussion

The recent change from subsidence to uplift helps to constrain models of surface deformation at Yellowstone. Dzurisin et al. (1990) proposed two end-member models to explain uplift and subsidence of the caldera floor. In the first, injection of basalt near the base of a cooling rhyolite magma system is the primary cause of uplift. Higher in the magma system, rhyolite crystallizes and releases its volatile constituents (gas + brine) into the shallow hydrothermal system. Uplift stops and subsidence starts whenever the supply rate of basalt is less than the subsidence rate produced by crystallization of rhyolite and associated fluid loss.

In the second model, uplift is caused primarily by pressurization of the deep hydrothermal system by magmatic volatiles released during crystallization of rhyolite and then trapped at lithostatic pressure beneath an impermeable self-sealed zone. Mineral deposition and high-temperature annealing combine to eliminate fracture permeability in the self-sealed zone. Subsidence occurs as a result of episodic hydrofracturing and injection of pore fluid from the deep lithostatic-pressure zone into a shallow hydrostatic-pressure zone. This process might account for the intense earthquake swarm that accompanied the beginning of subsidence in 1995-96, but it does not explain the occurrence of a similar swarm in the same area immediately before the resumption of uplift in 1995-96.

In this context, uplift since 1995 reflects either an increase in the rate of basalt injection or the re-sealing and pressurization of the deep hydrothermal system. The interferograms show that uplift started in the northeast half of the caldera sometime between August 1995 and September 1996, while the southwest half was still subsiding. By June 1997, uplift had spread throughout the entire caldera. Earlier, the center of subsidence moved from the northeast half of the caldera to the southwest half in less than 2 years. The rapidity with which these changes occurred would seem to favor a low-viscosity fluid such as magmatic gas + brine over a more viscous fluid such as magma.

Wicks et al. (1998) noted that migration of uplift from the Sour Creek dome to the Mallard Lake dome during 1995-97 suggests that the source of driving pressure lies beneath the Sour Creek dome. They modeled the process as laminar Poiseuille flow in a cylindrical pipe and showed that, to produce the observed flux of about 0.016 km^3/yr, the pipe radius would be about 14 m for rhyolite (= fluid viscosity = 10^8 Pa-s), 0.14 m for basalt (= 1 Pa-s), and a few millimeters for water or steam (= 10^{-4}-10^{-6} respectively). In other words, the observed flux is much easier to achieve with a low-viscosity fluid such as magmatic gas or brine.

This interpretation is generally consistent with a model for the location and shape of the deformation source based on the interferograms. Wicks et al. (1998) modeled the deformation source for the period from June 1993 to August 1995 as two horizontal tabular bodies located beneath the resurgent domes at 8.5 ± 4 km depth. This depth range includes the interface between the upper part of Yellowstone's magmatic system and the lower part of its hydrothermal system. Fournier (1998) envisions that plastic flow and mineral deposition combine to form a self-sealed layer at about 5 km depth. This layer serves as the interface between the magmatic and hydrothermal systems by regulating the upward flow of fluids and heat.

Rapid, sub-horizontal movement of the subsidence source from one half of the caldera to the other suggests to us that accumulation and lateral migration of magmatic and hydrothermal fluids play an important role in causing surface deformation at Yellowstone. Nonetheless, the cause of Yellowstone's remarkable crustal motions remains open to other interpretations, and additional geodetic studies are needed to resolve the issue.

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Figure Captions

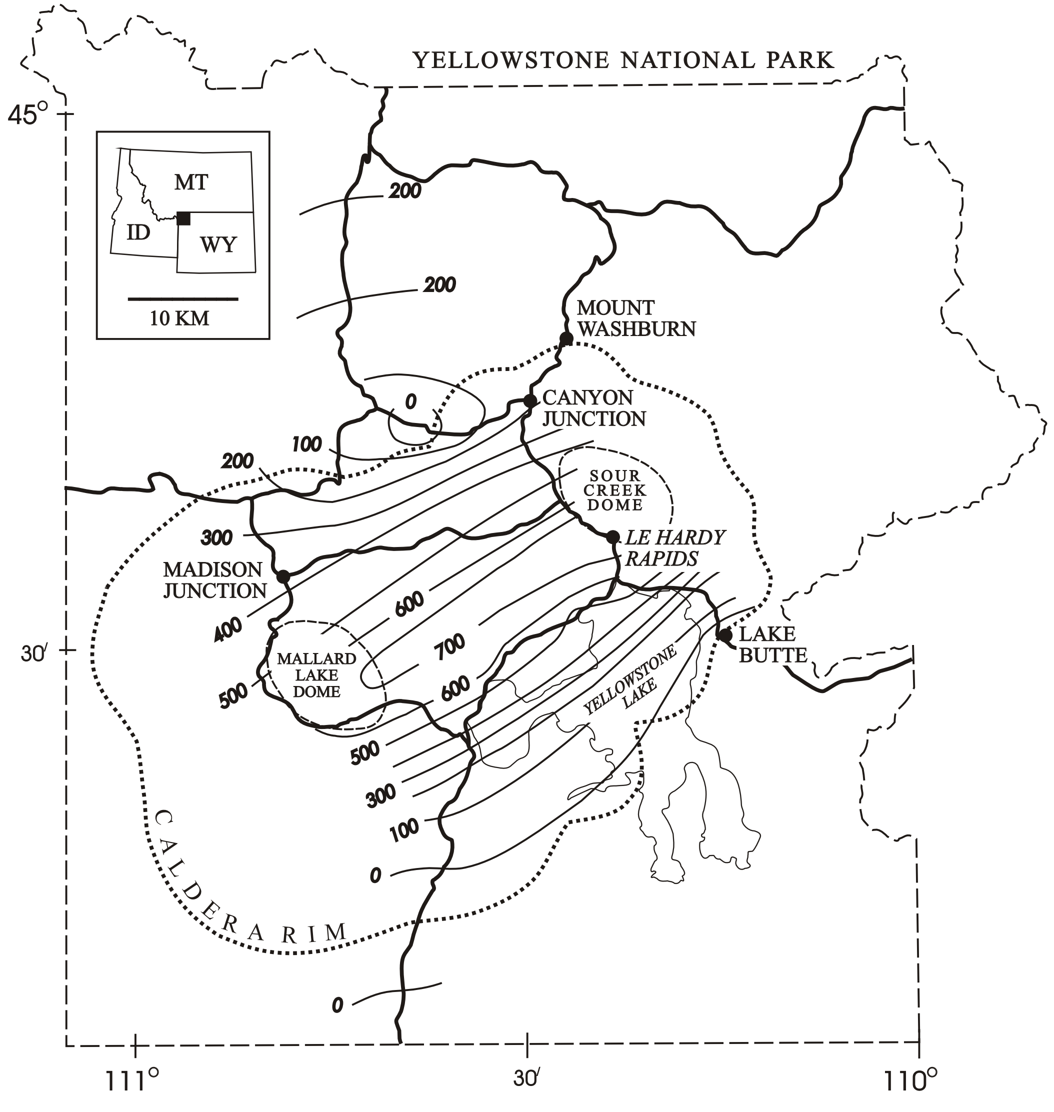
Fig. 1 The Yellowstone leveling network (heavy lines), Yellowstone National Park boundary (dashed line), and approximate outlines of the 0.63 Ma Yellowstone caldera and the Mallard Lake and Sour Creek resurgent domes (dotted lines). Most or all of the leveling network was measured in 1923, 1975-77, and 1987. In addition, the traverse between Lake Butte and Canyon Junction was measured annually from 1983 to 1998, except 1994, 1996, and 1997. Starting in 1989, annual surveys were extended northward from Canyon Junction to Mount Washburn. Also shown are uplift contours, in millimeters (thin lines), derived from a comparison of the 1923 and 1975-77 leveling surveys by Pelton and Smith (1982)

Fig. 2 Four interferograms of the Yellowstone region constructed by Wicks et al. (1998) from ERS-1 and ERS-2 radar images. The range of colors from violet to red, shown in the color bar, corresponds to one cycle of phase from 0 to 2 (one fringe). Each fringe represents ~28 mm of displacement between a point on the ground at the satellite. The first three interferograms are sequential, whereas the time periods covered by the third and fourth overlap. **A**, August 1992 to June 1993: This image shows over 30 mm of subsidence centered in the northeast half of the caldera in the vicinity of the Sour Creek resurgent dome. **B**, June 1993 to August 1995: The center of subsidence (~40 mm maximum) has shifted in this image to the southwest half of the caldera near the Mallard Lake resurgent dome. **C**, August 1995 to September 1996: The fringe pattern in the northeast half of the caldera in this image corresponds to ~20 mm of uplift in the vicinity of the Sour Creek dome (note the reversed color sequence toward the center of the fringe pattern relative to A and B). **D**, July 1995 to June 1997: In this image, uplift extends throughout the central part of the caldera (maximum ~30 mm)

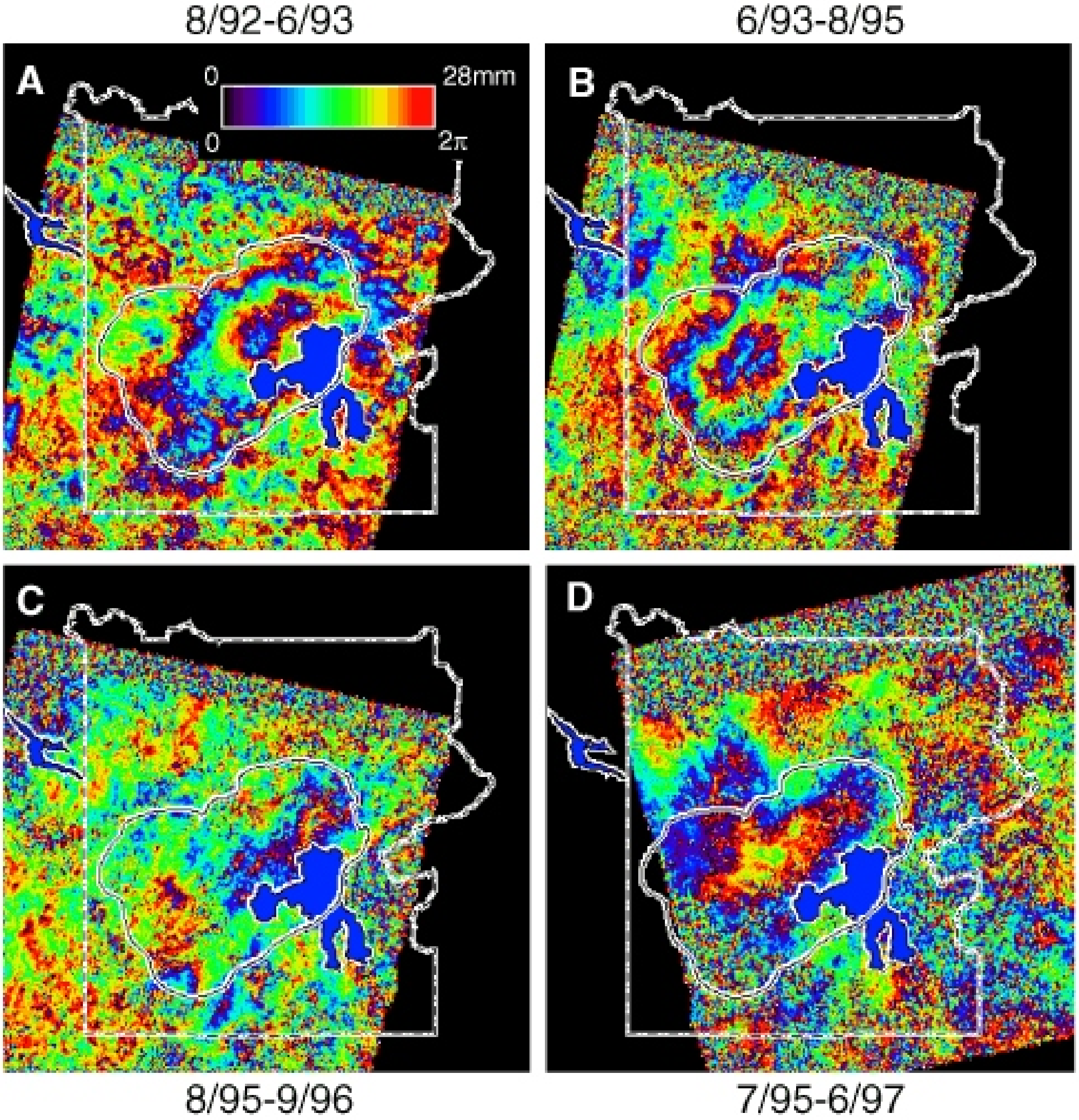
Fig. 3 Comparison of vertical displacements along the Lake Butte - Mount Washburn leveling traverse measured by satellite interferometric synthetic aperture radar (circles; Wicks et al. 1998) and leveling (squares; this study). Also shown is a topographic profile along the traverse (triangles), which crosses the caldera from rim to rim. Error bars represent one standard deviation from uncorrected random error in the leveling surveys. The InSAR data near the south end of the traverse (*d* = 0-10 km) are noisy and may not give a reliable estimate of surface movements. Note the different time periods covered by InSAR and leveling observations

Fig. 4 Vertical displacement profiles along the Lake Butte - Mount Washburn leveling traverse measured by successive surveys between 1984 and 1998. Benchmark 36 MDC near Lake Butte (*d* = 0) was held fixed. Error bars shown for 1995-98 represent one standard deviation from uncorrected random error in the leveling surveys. Random error accumulates as the square root of the distance leveled, so the same error bars apply to all of the profiles. The 1984-88 surveys were conducted between 36 MDC near Lake Butte and 11 MDC at Canyon Junction, whereas the 1989-98 surveys extended about 5 km farther north to R 366 at Mount Washburn. Therefore, all of the displacement profiles except 1995-98 end at 11 MDC rather than R 366

Fig. 5 History of elevation changes at DA 3 near Le Hardy Rapids and 11 MDC at Canyon Junction relative to 36 MDC near Lake Butte for the period 1976-98. Data for both benchmarks are plotted at the same scale, with error bars corresponding to the marks' respective distances from 36 MDC. Displacements at 11 MDC, near the northeast rim of the caldera, are generally much smaller than those at DA 3 in the middle of the caldera near Le Hardy Rapids. There is a tendency for the two marks to move in the same direction, with some obvious exceptions (1986-88 and 1989-90). We note that 11 MDC seems to have moved distinctly downward when subsidence began in 1985-86 and upward when uplift resumed in 1995-98. Nonetheless, the most likely explanation for these movements is uncorrected leveling error



Dzurisin, Wicks, and Thatcher, Yellowstone Leveling and InSAR Ms., Fig. 1



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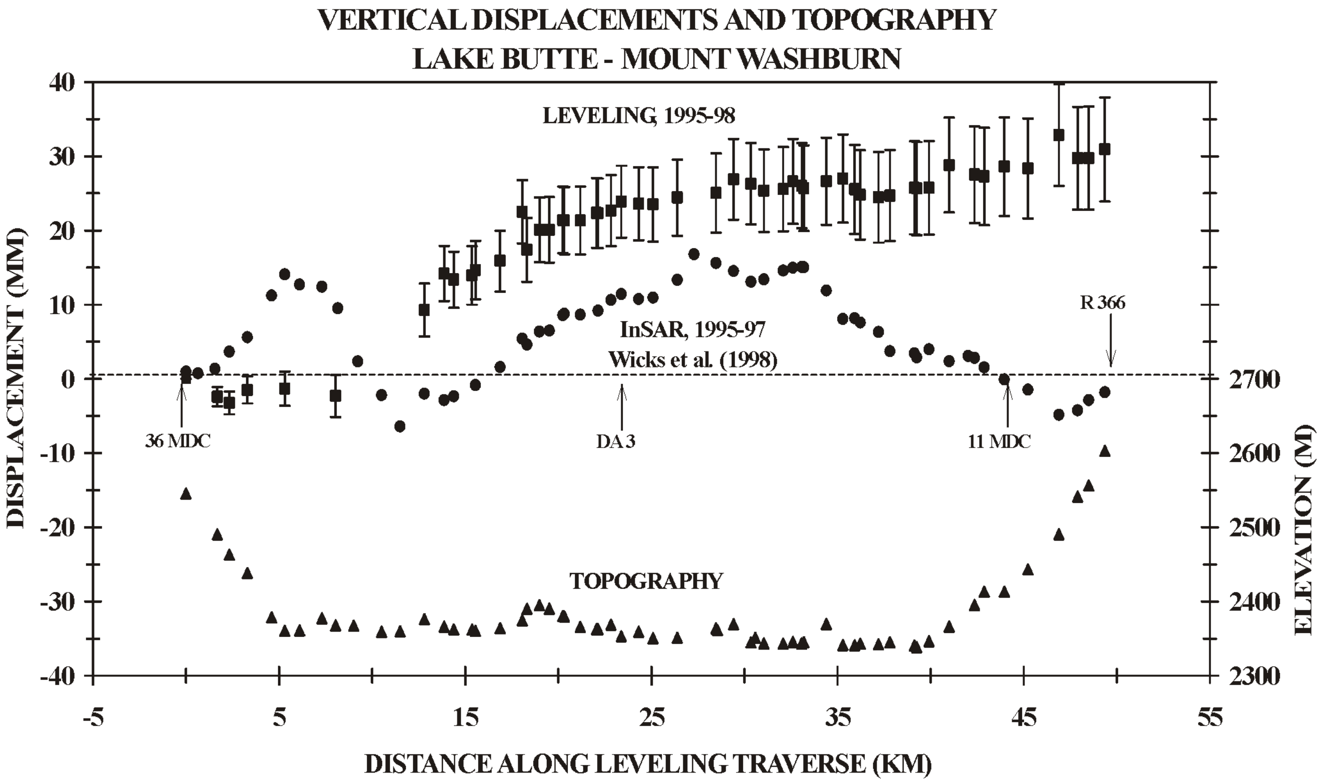
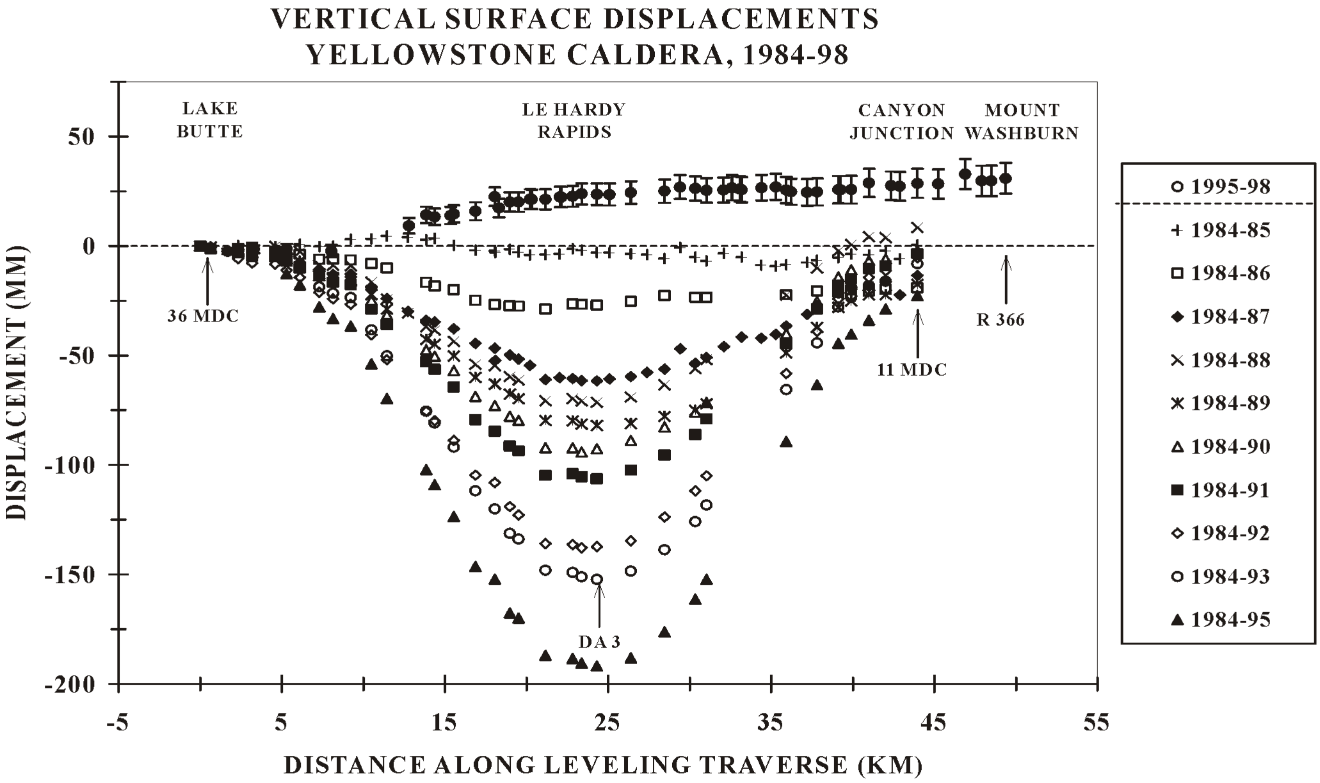
7/95-6/97


VERTICAL DISPLACEMENTS AND TOPOGRAPHY
LAKE BUTTE - MOUNT WASHBURN
LEVELING, 1995-98
InSAR, 1995-97
Wicks et al. (1998)
TOPOGRAPHY
36 MDC
DA 3
11 MDC
R 366
DISPLACEMENT (MM)
ELEVATION (M)
DISTANCE ALONG LEVELING TRAVERSE (KM)
40
30
20
10
0
-10
-20
-30
-40
2700
2600
2500
2400
2300
-5
5
15
25
35
45
55


VERTICAL SURFACE DISPLACEMENTS
YELLOWSTONE CALDERA, 1984-98
LAKE BUTTE
LE HARDY RAPIDS
CANYON JUNCTION
MOUNT WASHBURN
36 MDC
DA 3
11 MDC
R 366
DISPLACEMENT (MM)
50
0
-50
-100
-150
-200
-5
5
15
25
35
45
55
DISTANCE ALONG LEVELING TRAVERSE (KM)
○ 1995-98
+ 1984-85
□ 1984-86
◆ 1984-87
× 1984-88
✱ 1984-89
△ 1984-90
■ 1984-91
◇ 1984-92
○ 1984-93
▲ 1984-95

ELEVATION CHANGES AT LE HARDY RAPIDS AND CANYON JUNCTION RELATIVE TO LAKE BUTTE, 1976-98