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SCIENCE

# Recent Crustal Uplift in Yellowstone National Park

Abstract. *Comparison of precise leveling measurements made in 1923 with those made in 1975, 1976, and 1977 reveals that the 600,000-year-old Yellowstone caldera is being uplifted relative to its surroundings. Maximum relative uplift since 1923 is in excess of 700 millimeters—about 14 millimeters vertically per year. The most likely cause of this rapid and unusually large surface deformation is a recent influx of molten or partially molten material to a location within the crust beneath Yellowstone National Park.*

Yellowstone National Park is an important area of Pleistocene intracontinental volcanism; three similar cycles of intense silicic volcanism have occurred there in the past 2 million years (*1*, *2*). The latest cycle began about 1.2 million years ago with the generation of two adjacent ring-fracture zones in central Yellowstone above two magma chambers that were probably connected at deeper levels with a larger magma body. Growth of the ring-fracture zones and minor rhyolitic volcanism eventually led to an explosive eruption of rhyolitic pumice and ash (1000 $km^3$) 600,000 years ago. Immediately after this eruption the roofs overlying the two magma chambers collapsed to form the elliptical Yellowstone caldera. A resurgent dome in the northeastern part of the caldera developed shortly after formation of the caldera; another resurgent dome in the southwestern part, near Old Faithful, appears to be the result of renewed magmatic activity beginning 150,000 years ago. Rhyolite flows as young as 70,000 years are associated with this recent activity.

In this report we present evidence for recent uplift of the Yellowstone caldera in excess of 700 mm (about 14 mm/year). This rapid and unusually large vertical movement is of considerable interest because geophysical studies indicate that a hot upper crustal body, which may be at least partially molten, still underlies the

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caldera (3-8). Moreover, the possibility of a volcanic eruption in Yellowstone in the future cannot be ignored (2).

The basis for vertical crustal movement studies in Yellowstone was established in 1923 when level lines of second-order precision were observed throughout the park by the U.S. Coast and Geodetic Survey (9). Nearly all of the 1923 level lines were reobserved to first-order precision by the U.S. Geological Survey (Topographic Division) in cooperation with the University of Utah during the summers of 1975, 1976, and 1977 (10). Assuming that the benchmarks did not move relative to one another between 1975 and 1977, a 52-year interval (1923 to 1975) has been defined for which the following quantities may be computed for each benchmark relative to an arbitrarily chosen reference level: (i) the change in height ($\Delta h$) and (ii) the average relative vertical velocity ($V$).

A contour map of $\Delta h$ and $V$ computed relative to benchmark K12 is shown in Fig. 1. The principal feature of this map is an elongated uplift that approximately coincides with the Yellowstone caldera. Benchmarks with $\Delta h$ greater than 300 mm ($V$ = 5.8 mm/year) are confined to the caldera, and benchmarks located along the line between Fishing Bridge and West Thumb indicate that the zone of largest $\Delta h$ (greater than 500 mm) extends along a northeast trend parallel to the caldera axis. The maximum $\Delta h$ is 726 mm ($V$ = 14.0 mm/year) and occurs at a benchmark 3 km north of Fishing Bridge near the margin of one of the resurgent domes. These positive $\Delta h$ values are among the largest that have been discovered in a continental setting far from a plate boundary (except in landslides and man-made disturbances). The nature of the uplift northeast and southwest of the caldera rim is unknown because of the absence of leveling data for those areas.

The comparison of repeated leveling measurements has become an important technique for detecting vertical surface movements, but its use demands careful error analysis. The accuracy of a $\Delta h$ value depends on the accuracy of the height difference measured in each of the two constituent levelings. For the levelings in 1923 and 1975, 1976, and 1977, the random error of a measured height difference was assumed to be normally distributed with mean zero and standard deviation equal to $\alpha (L/N)^{1/2}$, where $L$ is the distance between the two points connected by leveling, $\alpha$ is a monotonically increasing function of $L$ that describes the quality of the leveling, and $N$ is the number of repeated measurements made of the height difference during the leveling. The assumption of distance-dependent $\alpha$ is an attempt to include undefined systematic errors that can accumulate with distance in the random error (11). Since this statistical model cannot represent systematic errors that accumulate with height, we checked the $\Delta h$ data in profile form for a correlation with topography. For example, the profile across the caldera between benchmarks Q13 and B14 (Fig. 2a) shows that although large $\Delta h$ values occur in areas of high elevation, there is no consistent correlation between $\Delta h$ and the topography. We were also unable to find a straightforward correlation between $\Delta h$ and topography along other profiles. This evidence does not rule out the possibility of systematic errors accumulating with height in the 1923 and 1975-1977 levelings, but it does indicate that such errors are probably not a significant component of the $\Delta h$ data.

Statistical estimates for $\alpha$ were obtained from discrepancies between the forward and backward levelings of a section between benchmarks ($0 < L < 2$ km) and from circuit closures where $L \doteq 125$ km (12). Values of $\alpha$ at intermediate distances were computed by straight-line interpolation between the statistically estimated endpoints (Fig. 2b). For small $L$ we obtained $\alpha(1923) = 3.6$ mm/km$^{1/2}$ and $\alpha(1975\text{-}1977) = 1.3$ mm/km$^{1/2}$; these are typical $\alpha$ values for the order and date of the leveling work considered here. The 1975-1977 circuit closures are all within a few millimeters of the random error predicted by $\alpha(1975\text{-}1977) = 1.3$ mm/km$^{1/2}$, $L = 125$ km, and $N = 2$, indicating that $\alpha(1975\text{-}1977)$ is a constant and that systematic error accumulating with distance is probably not a factor in the leveling data for those years. In contrast with this result, the 1923 circuit closures are four times the expected value for $\alpha(1923) = 3.6$ mm/km$^{1/2}$, $L = 125$ km, and $N = 1$, suggest-

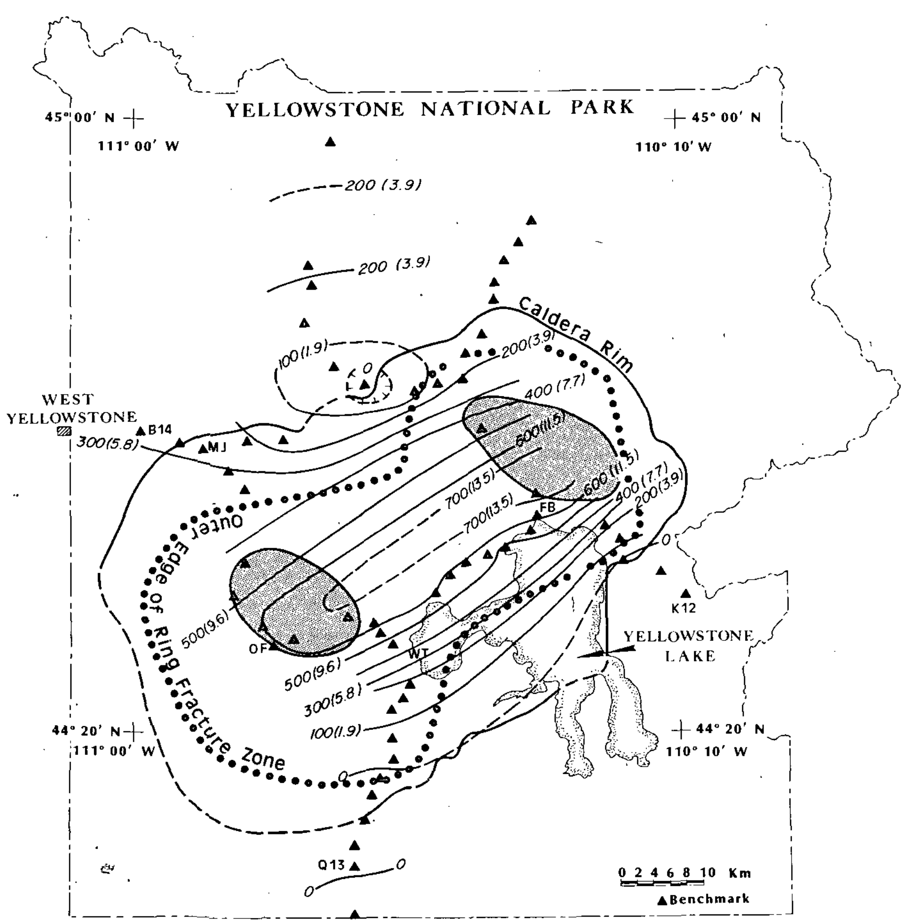


Fig. 1. Contour map of $\Delta h$ for the time interval 1923 to 1975. Reference point is benchmark K12. Contour interval is 100 mm; corresponding values of $V$ are given in parentheses in millimeters per year. Shaded areas are resurgent domes. Abbreviations: *FB*, Fishing Bridge; *MJ*, Madison Junction; *OF*, Old Faithful; and *WT*, West Thumb.

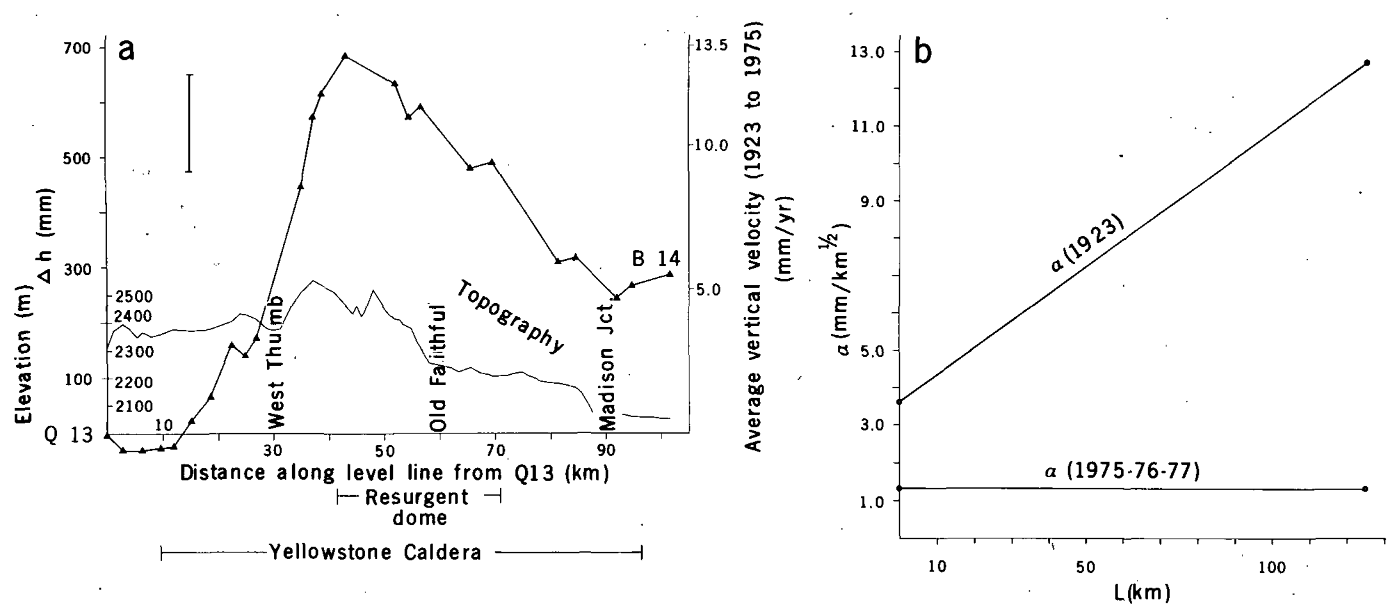


Fig. 2. (a) Profile of $\Delta h$, $V$, and topography for time interval 1923 to 1975. Bar length represents twice the average of the standard deviations of $\Delta h$ and $V$ profile values. (b) Plot of estimated $\alpha$ values.

ing that systematic error did accumulate with distance in 1923. The 95 percent confidence interval for $\alpha(1923)$ at 125 km is unavoidably large because of the small sample (only two circuits), but 12.7 mm/km$^{1/2}$ is the best point estimate and has been used as a means of including the undefined 1923 distance-dependent systematic error in the random error. We investigated the possibility that the large 1923 circuit closures are the result of a failure to make orthometric corrections to the observed height difference data. The maximum circuit closure resulting from a failure to make orthometric corrections during otherwise errorless leveling around a 125-km circuit in Yellowstone was estimated to be approximately 12 mm. The 1923 circuit closures are an order of magnitude larger than 12 mm and therefore must be due to some other source of systematic error.

The standard deviation of $\Delta h$ is given by the square root of the sum of the squares of the standard deviations for the two constituent measured height differences. The mean of the $\Delta h$ standard deviations for the 60 1923 benchmarks recovered for use in this study is 74.7 mm and the maximum is 121.9 mm; corresponding mean and maximum standard deviations for $V$ are 1.4 and 2.3 mm/year, respectively. We therefore feel that the $\Delta h$ and $V$ values for most of the recovered 1923 benchmarks are statistically significant.

As mentioned above, the uplift at Yellowstone occurs in close association with the Yellowstone caldera, a known center of extensive Pleistocene volcanism. This coincidence immediately suggests that the uplift is the result of magmatic processes operating in the crust beneath the caldera. An increase in pressure acting against the boundary-enclosing magma (or partially molten material) is a basic mechanism for uplift in volcanic areas. The increase in pressure could result from an influx of molten or partially molten material from deeper levels, or from intense vesiculation. If a significant change in temperature accompanies either process, then thermal expansion or contraction may become an important effect.

Uplift mechanisms that are not related to magmatic processes but could produce the vertical movements in Yellowstone include horizontal compressive stress associated with active tectonics, dilatancy, and glacioisostatic rebound. The predominance of Quaternary normal faults (*13*) and normal earthquake fault-plane solutions (*7*) for the Yellowstone area is an indication that the direction of regional maximum compressive stress is vertical. This evidence argues against interpreting the uplift at Yellowstone as a result of tectonic horizontal compressive stress. If dilatancy is responsible for the uplift, then it must be developed to the stage at which expansion of a crustal body has occurred. A dilatant mass 5 km thick beneath the caldera must undergo a volumetric strain ($\Delta v/v$, where $v$ is volume) of about 0.0001 to be consistent with an average uplift of 400 mm (*14*). If we may apply the results of laboratory experiments, this volumetric strain would require an unreasonably large stress difference (> 5 kbar) for granite at a confining pressure of 1 kbar (*15*), assuming that dilatancy occurs in situ in competent rock by the opening of microfractures. Thus either dilatancy is not responsible for the uplift, or dilatancy in situ may be occurring by a process that requires a much lower stress difference for the onset of volume increase.

A prominent terrace was formed not more that 9000 years ago around Yellowstone Lake at a level 18 to 20 m above the present shoreline (*16*). The fact that the terrace maintains a nearly constant elevation around the lake is of critical importance because this means that the entire terrace has experienced the same net vertical displacement. The contemporary pattern of average relative vertical velocities in Yellowstone thus cannot have been maintained for more than a few hundred years; otherwise the portion of the terrace located near Fishing Bridge would now be measurably tilted up with respect to another portion of the same terrace about 12 km to the southeast. This information provides a strong argument against any interpretation of the Yellowstone uplift which is based on long-term maintenance of the modern pattern of relative vertical velocities such as glacioisostatic rebound.

The extremely high convective heat loss in Yellowstone National Park ($4.02 \times 10^{16}$ cal/year) can be explained by the crystallization and cooling of 0.1 km$^3$ of rhyolite magma annually from 900° to 500°C (*17*). If we adopt a simplified cooling history for a rhyolite magma body to explain the heat loss at Yellowstone, then in the 600,000 years since formation of the caldera, a layer of solid granite 26 km thick should have formed beneath the caldera. This conclusion is inconsistent with anomalously low seismic velocities deduced from relative teleseismic P-wave delays, which suggest a partial melt in the upper crust (*5*, *6*). One way to resolve this problem is to postulate a sporadic input of molten or partially molten material from the magmatic source. Such inputs might occasionally produce a temporary swelling of the surface followed by stress relaxation. On this basis it seems reasonable to interpret the contemporary uplift at Yellowstone as one phase in a series of deformation episodes centered on the caldera and related to an ongoing process of intrusion. This hypothesis does not conflict with the youth of the uplift or the fact that there has been no eruption in Yellowstone for 70,000 years (*2*). It has been suggested that intrusion of magma may be responsible for contemporary doming (3 to 5 mm/year) of an 8000-$km^2$ area just northwest of Yellowstone (*18*), but whether there is any relationship between this doming and the uplift at Yellowstone is an unsettled question.

There is a possibility that the uplift at Yellowstone represents a new magmatic insurgence heralding the start of a fourth volcanic cycle. At this time we cannot distinguish this possibility from one in which only late third-cycle volcanism occurs or from one in which the intrusion of mobile material simply deforms the surface without eruption. If a new eruption were to occur, it would typically be preceded by such phenomena as increased numbers of earthquake swarms, increased hydrothermal activity, and further deformation of the surface.

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**References and Notes**

1. R. L. Christiansen and H. R. Blank, Jr., *U.S. Geol. Surv. Prof. Pap. 729-B* (1972).
2. R. L. Christiansen, U.S. Geological Survey, personal communication.
3. R. B. Smith, R. T. Shuey, R. O. Freidline, R. M. Otis, L. B. Alley, *Geology* **2**, 451 (1974).
4. G. P. Eaton, R. L. Christiansen, H. M. Iyer, A. M. Pitt, D. R. Mabey, H. R. Blank, Jr., I. Zietz, M. E. Gettings, *Science* **188**, 787 (1975).
5. H. M. Iyer and R. M. Stewart, in *Proceedings of the Chapman Conference on Partial Melting in the Upper Mantle* (State of Oregon Department of Geology and Mineral Industries, Portland, 1977), pp. 281-299.
6. A. M. Pitt and C. Weaver [*Earthquake Notes* **49**, 11 (1978)] suggested that the large (1.5-second) relative teleseismic P-wave delays measured within the Yellowstone caldera (*5*) may be a result of anomalously low seismic velocities in the mantle rather than in the crust.
7. R. B. Smith, R. T. Shuey, J. R. Pelton, J. P. Bailey, *J. Geophys. Res.* **82**, 3665 (1977).
8. P. Morgan, D. D. Blackwell, R. E. Spafford, R. B. Smith, *ibid.*, p. 3719.
9. Approximately 15 percent of the sections between benchmarks were double-run in the 1923 leveling.
10. All sections between benchmarks were double-run in the 1975-1977 levelings.
11. G. Bomford, *Geodesy* (Oxford Univ. Press, London, 1971), pp. 244-246.
12. Three circuits with $L \doteq 125$ km were closed during the 1975-1977 levelings. Two circuits of this length were closed during the 1923 leveling.
13. *U.S. Geol. Surv. Misc. Geol. Invest. Map I-711* (1972).
14. The approximate maximum focal depth for inner caldera earthquakes is 5 km (*7*), suggesting that brittle failure cannot occur below that depth.
15. W. F. Brace, B. W. Paulding, Jr., C. Scholz, *J. Geophys. Res.* **71**, 3939 (1966).
16. G. M. Richmond, *U.S. Geol. Surv. Bull. 1427* (1976).
17. R. O. Fournier, D. E. White, A. H. Truesdell, in *Proceedings of the Second U.N. Symposium on Development and Use of Geothermal Resources* (Government Printing Office, Washington, D.C., 1976), vol. 1, pp. 731-739.
18. R. E. Reilinger, G. P. Citron, L. D. Brown, *J. Geophys. Res.* **82**, 5349 (1977).
19. This research was supported by U.S. Geological Survey, Geothermal Research Program grant 14-08-0001-G-438 and by National Science Foundation grant EAR-74-13848 A02. J.R.P. thanks the staff of the Department of Geology at Brigham Young University for their help during preparation of the manuscript.
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# RECENT CRUSTAL UPLIFT IN YELLOWSTONE NATIONAL PARK

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ABSTRACT

The comparison of precise leveling measurements made in 1923 and 1975-76-77 in Yellowstone National Park has disclosed uplift of the 600,000 year old Yellowstone caldera relative to its surroundings. Maximum relative uplift is in excess of +700 mm which corresponds to an average relative vertical velocity of approximately 14 mm/yr. The most likely cause of this rapid and unusually large surface deformation is a recent influx of molten or partially molten material to a location within the crust beneath Yellowstone.

The region of Yellowstone National Park is an important area of Pleistocene intracontinental volcanism; three similar cycles of intense silicic volcanism have occurred there in the last two million years (1-2). The third and latest cycle began about 1.2 million years ago with the generation of two adjacent ring-fracture zones in central Yellowstone above twin magma chambers which were probably connected at depth with a larger magma body. Growth of the ring-fracture zones and minor rhyolitic volcanism eventually led to the explosive eruption of 1,000 $km^3$ of rhyolitic pumice and ash 600,000 years ago. Immediately following this eruption the roofs overlying the two magma chambers collapsed to form the elliptical Yellowstone caldera. A resurgent dome in the northeastern part of the caldera developed shortly after caldera formation, while another resurgent dome in the southwestern part, near Old Faithful, appears to be the result of renewed magmatic activity beginning 150,000 years ago. Rhyolite flows as young as 70,000 years are associated with this most recent activity.

In this report we present evidence for recent uplift of the Yellowstone caldera with maximum relative vertical movements in excess of +700 mm and corresponding average relative vertical velocities of approximately 14 mm/yr. These rapid and unusually large vertical movements are of considerable interest because geophysical studies indicate that a hot upper crustal body which may be at least partially molten still underlies the caldera (3-8). Moreover, the possibility of a future Yellowstone volcanic eruption cannot be ignored (2).

The basis for modern vertical crustal movement studies in Yellowstone was established in 1923 when level lines of second-order precision were observed throughout the park by the U.S. Coast and Geodetic Survey (9). Nearly all of the 1923 level lines were reobserved to first-order precision by the U.S. Geological Survey Topographic Division in cooperation with the University of Utah during the summers of 1975, 1976, and 1977 (10). Under the assumption that the Yellowstone benchmarks did not move relative to one another between 1975 and 1977, a 52 year interval (1923-1975) is defined over which the following quantities may be computed for each benchmark relative to an arbitrary reference: (i) the change in observed height difference ($\Delta h$ mm), and (ii) the average relative vertical velocity $V = \Delta h/52$ mm/yr.

A contour map of $\Delta h$ and V computed relative to benchmark K12 is shown in Figure 1. The principal feature of this map is an elongate uplift approximately coincident with the Yellowstone caldera. Benchmarks with $\Delta h$ values greater than +300 mm (V = 5.8 mm/yr) are confined to the caldera, and benchmarks located along the line between Fishing Bridge and West Thumb indicate that the zone of largest $\Delta h$ (greater than +500 mm) extends along a northeast trend parallel to the caldera axis. The maximum $\Delta h$ value is +726 mm (V = 14.0 mm/yr) and occurs at a benchmark located 3 km north of Fishing Bridge near the margin of one of the resurgent domes. These $\Delta h$ values are among the largest positive values that have been discovered in a continental setting located far from a plate boundary (neglecting landslides and artificial disturbances). The nature of the uplift northeast and southwest of the caldera rim is unknown because of the absence of leveling data in those areas.

The comparison of repeat leveling measurements has become an important technique for detecting vertical surface movements, but its use demands careful error analysis. The accuracy of a $\Delta h$ value depends on the accuracy of the observed height difference measured in each of the two constituent levelings. For the Yellowstone levelings of 1923 and 1975-76-77, the random error of an observed height difference was assumed to be normally distributed with mean zero and standard deviation $\sigma = \alpha\,(L/N)^{1/2}$, where L is the distance between the two points connected by leveling, $\alpha$ is a monotonically increasing function of L which describes the quality of the leveling, and N is the number of repeat measurements made of the observed height difference during the leveling. The assumption of distance dependent $\alpha$ is an attempt to include undefined systematic errors which accumulate with distance in the random error (11). Since this statistical model cannot represent systematic errors which accumulate with height, we checked the $\Delta h$ data in profile form for a correlation with topography. As an example, the profile across the caldera between benchmarks Q13 and B14 (Figure 2a) shows that although large $\Delta h$ values occur in areas of high elevation, there is no consistently simple correlation between $\Delta h$ and topography. We were also unable to find straightforward correlation between $\Delta h$ and topography along other profiles. This evidence does not rule out the possibility of systematic errors accumulating with height in the 1923 and/or 1975-76-77 Yellowstone levelings, but it does indicate that such errors are probably not a significant component of the $\Delta h$ data.

Statistical estimates for $\alpha$ were obtained from discrepancies between the forward and backward levelings of a section between benchmarks ($0 < L < 2$ km), and from circuit closures where $L \doteq 125$ km (12). Values of $\alpha$ at intermediate distances were computed by straight line interpolation between the statistically estimated endpoints (Figure 2b). For small L we obtained $\alpha(1923) = 3.6$ mm/km$^{1/2}$ and $\alpha$(1975-76-77) = 1.3 mm/km$^{1/2}$; these are typical $\alpha$ values for the order and date of the leveling work considered here. The 1975-76-77 circuit closures are all within a few mm of the random error predicted by $\alpha$(1975-76-77) = 1.3 mm/km$^{1/2}$, $L = 125$ km, and $N = 2$, indicating that $\alpha$(1975-76-77) is a constant and that systematic error accumulating with distance is probably not a factor in the 1975-76-77 leveling data. In contrast with this result, the 1923 circuit closures are four times the expected value for $\alpha(1923) = 3.6$ mm/km$^{1/2}$, $L = 125$ km, and $N = 1$, suggesting that systematic error did accumulate with distance in 1923. The 95 percent confidence interval for $\alpha(1923)$ at 125 km is unavoidably large because of the small sample (only two circuits), but 12.7 mm/km$^{1/2}$ is the best point estimate, and this estimate has been used as a means of including the undefined 1923 distance-dependent systematic error in the random error. We investigated the possibility that the large 1923 circuit closures are the result of a failure to make orthometric corrections to the observed height difference data. The maximum circuit closure resulting from a failure to make orthometric corrections during otherwise errorless leveling around a 125 km circuit in Yellowstone was estimated to be approximately 12 mm. The 1923 circuit closures are an order of magnitude larger than 12 mm and therefore must be due to some other source of systematic error.

The standard deviation of Δh is given by the square root of the sum of the squares of the standard deviations for the two constitutent observed height differences. The mean of the Δh standard deviations for the sixty 1923 benchmarks recovered for use in this study is 74.7 mm and the maximum is 121.9mm; corresponding mean and maximum standard deviations for V are 1.4 mm/yr and 2.3 mm/yr respectively. We therefore feel that the Δh and V values for most of the recovered 1923 benchmarks are statistically significant.

As mentioned above, the Yellowstone uplift occurs in close association with the Yellowstone caldera, a recognized center of extensive Pleistocene volcanism. This coincidence immediately suggests that the uplift is the result of magmatic processes operating in the crust beneath the caldera. An increase in pressure acting against the boundary enclosing a magma (or partial melt) is a simple mechanism for uplift in volcanic source areas. The increase in pressure could be the result of an influx of molten or partially molten material from depth, or intense vesiculation. If a significant change in temperature accompanies either of these two processes, then thermal expansion or contraction may become an important effect.

Uplift mechanisms which are not related to magmatic processes but which could produce the observed vertical movements in Yellowstone include: horizontal compressive stress associated with active tectonics, dilatancy, and glacio-isostatic rebound. The predominance of Quaternary normal faults (13) and normal earthquake fault-plane solutions (7) for the Yellowstone area is an indication that the direction of regional maximum compressive stress is vertical. This evidence argues against interpreting the Yellowstone uplift as a result of tectonic horizontal compressive stress. If on the other hand dilatancy is responsible for the uplift, then it must be developed to a stage where volume expansion of a crustal body has actually taken place. A dilatant volume 5 km thick beneath the caldera must undergo a volumetric strain $\Delta v/v$ of about +0.0001 to be consistent with an average uplift of +400 mm (14). If we can extrapolate the results of laboratory experiments, this volumetric strain would require an unreasonably large stress difference (>5 kbar) for granite at 1 kbar confining pressure (15), assuming in-situ dilatancy occurs in competent rock by the opening of microfractures. Thus either dilatancy is not responsible for the uplift, or in-situ dilatancy may be occurring by a process that requires a much lower stress difference for the onset of volume increase.

A prominent lake terrace was formed not more than 9,000 years ago around Yellowstone Lake at a level 18-20 m above the present shoreline (16). The fact that the terrace maintains a nearly constant elevation around the lake is of critical importance, because this means that the entire terrace has experienced the same net vertical displacement. The contemporary pattern of average relative vertical velocities in Yellowstone thus cannot have been maintained for more than a few hundred years; otherwise the portion of the terrace located near Fishing Bridge would now be measurably tilted up with respect to another portion of the same terrace located about 12 km to the southeast (Figure 1). This information provides a strong argument against any interpretation of the Yellowstone uplift which requires long-term maintenance of the modern pattern of relative vertical velocities such as glacio-isostatic rebound.

The extremely high convective heat loss measured for Yellowstone National Park ($4.02 \times 10^{16}$ cal/yr) can be supplied by the crystallization and cooling of 0.1 $km^3$/yr of rhyolite magma from 900°C to 500°C (17). If we adopt a very simple cooling history for a rhyolite magma body to explain the Yellowstone heat loss, then in the 600,000 years that have elapsed since caldera formation a layer of solid granite 26 km thick should have formed beneath the caldera. This conclusion is inconsistent with anomalously low seismic velocities deduced from relative teleseismic P-wave delays which suggest a partial melt in the upper crust (5-6). One way to resolve the apparent difficulty is to postulate a sporadic input of molten material or partially molten material from the source region. The postulated input of mobile material might occasionally produce a temporary swelling of the surface followed by stress relaxation. On this basis it seems reasonable to interpret the contemporary Yellowstone uplift as one phase in a series of deformation episodes centered on the caldera and related to an ongoing process of intrusion. This hypothesis is not in conflict with the youth of the observed uplift or the fact that there has been no eruption in Yellowstone for 70,000 years (2). It has been suggested that magma intrusion may be responsible for contemporary doming (3-5 mm/yr) of an 8,000 $km^2$ area located just northwest of Yellowstone (18), but the relationship that could exist between this doming and the Yellowstone uplift is an unsettled question.

There is a possibility that the Yellowstone uplift represents a new magmatic insurgence heralding the start of a fourth volcanic cycle. At this time we cannot distinguish this possibility from one in which only late third-cycle volcanism is to be expected, or from one in which the intrusion of mobile material simply deforms the surface without eruption. If a new eruption in Yellowstone were to occur, we would expect that it would be accompanied by precursory phenomena such as increased numbers of earthquake swarms, increased hydrothermal activity, and further surface deformation.

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## REFERENCES AND NOTES

1. R. L. Christiansen and H. R. Blank, Jr., U. S. Geol. Surv. Prof. Pap. 729-B (1972).
2. R. L. Christiansen, U. S. Geol. Survey, personal communication (1979).
3. R. B. Smith, R. T. Shuey, R. O. Freidline, R. M. Otis, L. B. Alley, Geology 2, 451 (1974).
4. G. P. Eaton, R. L. Christiansen, H. M. Iyer, A. M. Pitt, D. R. Mabey, H. R. Blank, Jr., I. Zietz, M. E. Gettings, Science 188, 787 (1975).
5. H. M. Iyer and R. M. Stewart, in Proceedings of the Chapman Conference on Partial Melting in the Upper Mantle (State of Oregon Department of Geology and Mineral Industries, Portland, 1977), pp.281-299.
6. A. Pitt and C. Weaver [Earthquake Notes 49, 11(1978)] have suggested that the large (1.5 second) relative teleseismic P-wave delays observed within the Yellowstone caldera (5) may be a result of anomalously low seismic velocities in the mantle, rather than in the crust.
7. R. B. Smith, R. T. Shuey, J. R. Pelton, J. P. Bailey, J. Geophys. Res. 82, 3665 (1977).
8. P. Morgan, D. D. Blackwell, R. E. Spafford, J. Geophys. Res. 82, 3719 (1977).
9. Approximately 15 percent of the sections between benchmarks were double-run in the 1923 leveling.
10. All sections between benchmarks were double-run in the 1975-76-77 levelings.
11. G. Bomford, Geodesy (Oxford, London, 1971), pp. 244-246.
12. Three circuits with L ≐ 125 km were closed during the 1975-76-77 leveling. Two circuits of this length were closed during the 1923 leveling.
13. U. S. Geol. Surv. Misc. Geol. Invest. Map I-711 (1972).
14. Five kilometers is the approximate maximum focal depth for inner-caldera earthquakes (7), suggesting that brittle failure cannot occur below that depth.
15. W. F. Brace, B. W. Paulding, Jr., C. Scholz, J. Geophys. Res. 71, 3939 (1966).
16. G. M. Richmond, U. S. Geol. Surv. Bull. 1427 (1976).
17. R. O. Fournier, D. E. White, A. H. Truesdell, in Proceedings of the Second U. N. Symposium on Development and Use of Geothermal Resources (U. S. Government Printing Office, Washington, D. C., 1976), vol. 1, pp. 731-739.
18. R. E. Reilinger, G. P. Citron, L. D. Brown, J. Geophys. Res. 82, 5349 (1977).
19. This research was supported by the U. S. Geological Survey, Geothermal Research Program, Grant No. 14-08-0001-G-438, and by the National Science Foundation, Grant No. EAR-74-13848 A02. J. R. Pelton thanks the staff of the Geology department at Brigham Young University for help rendered during manuscript preparation.

# FIGURE LEGENDS

Figure 1. Map of $\Delta h$ for time interval 1923 to 1975. Reference is benchmark K12. Contour interval is 100mm; corresponding values of V given in mm/yr in parentheses. Abbreviations: FB-Fishing Bridge, MJ-Madison Junction, OF-Old Faithful, WT-West Thumb. Shaded areas are resurgent domes.

Figure 2. (a) Profile of $\Delta h$, V, and topography for time interval 1923 to 1975. Length of bar represents twice the average standard deviation of the $\Delta h$ and V profile values.

(b) Plot of estimated $\alpha$ values.

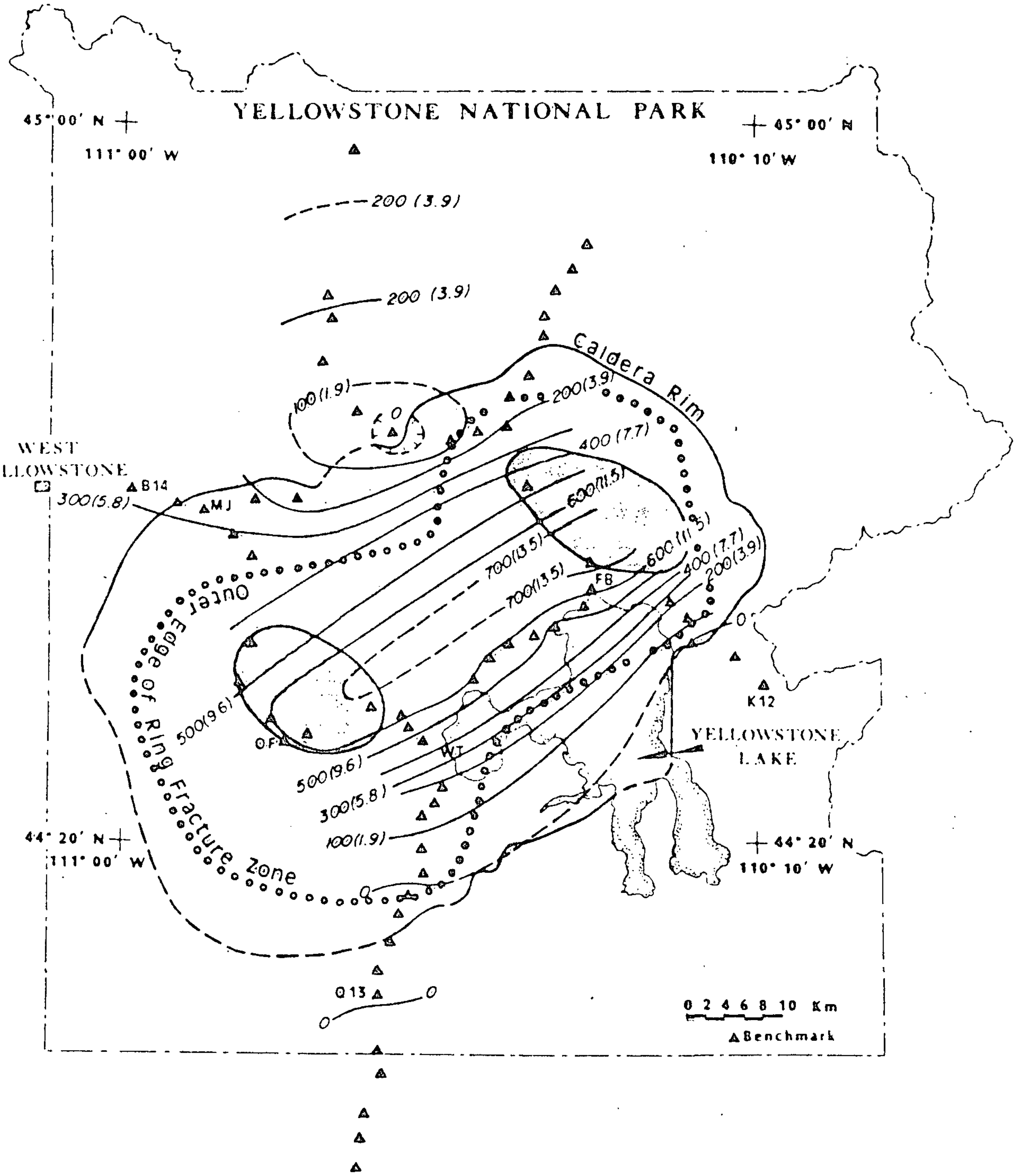
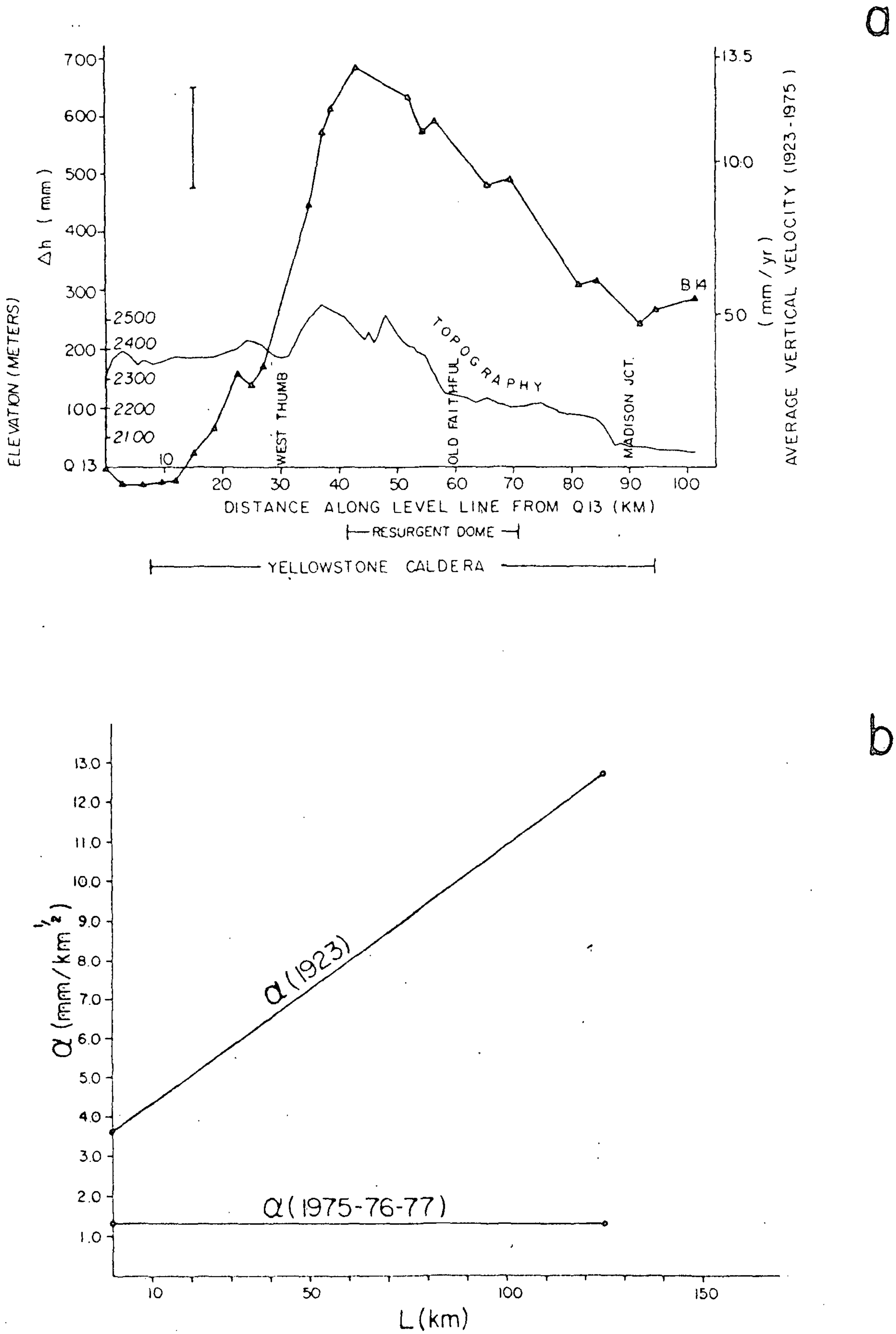

YELLOWSTONE NATIONAL PARK
45° 00′ N
111° 00′ W
45° 00′ N
110° 10′ W
200 (3.9)
200 (3.9)
100 (1.9)
0
Caldera Rim
200 (3.9)
400 (7.7)
WEST YELLOWSTONE
B14
MJ
300 (5.8)
600 (11.5)
700 (13.5)
700 (13.5)
600 (11.5)
400 (7.7)
200 (3.9)
FB
Outer Edge of Ring Fracture Zone
500 (9.6)
OF
500 (9.6)
WT
300 (5.8)
100 (1.9)
K12
YELLOWSTONE LAKE
44° 20′ N
111° 00′ W
44° 20′ N
110° 10′ W
Q13
0
0
0 2 4 6 8 10 Km
Benchmark

FIGURE 1



a
700
600
500
400
300
200
100
Δh ( mm )
ELEVATION (METERS)
2500
2400
2300
2200
2100
Q 13
10
B 14
13.5
10.0
5.0
( mm / yr )
AVERAGE VERTICAL VELOCITY (1923-1975)
TOPOGRAPHY
WEST THUMB
OLD FAITHFUL
MADISON JCT.
20
30
40
50
60
70
80
90
100
DISTANCE ALONG LEVEL LINE FROM Q13 (KM)
RESURGENT DOME
YELLOWSTONE CALDERA
b
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
α (mm/km^½)
α (1923)
α (1975-76-77)
10
50
100
150
L (km)


FIGURE 2

THE UNIVERSITY OF UTAH

COLLEGE OF MINES
AND MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 MINERAL SCIENCE BUILDING

September 27, 1979

Dr. Mike Wright
Earth Science Lab
UURI
Campus

Dear Mike:

We thought that because of your interest in crustal deformation that you would be interested in the results of some of our recent research dealing with uplift measurements and precision gravity measurements at Yellowstone National Park. This research was sponsored by the Geothermal Research Program of the U.S. Geological Survey.

We would appreciate receiving copies of your reprints and reports in these topic areas.

Good luck in your work. If you plan on passing through or over Salt Lake City, we would be happy to have you visit our department.

Sincerely,

Bob Bear Trap S.

Robert B. Smith
Professor of Geophysics

dl

Enclosures