

# InSAR Observations of the 2024 Biscuit Basin Hydrothermal Explosion

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## Abstract

The July 23, 2024 hydrothermal explosion at Biscuit Basin, Yellowstone Park, raised questions about whether surface deformation detectable by Interferometric Synthetic Aperture Radar (InSAR) could have provided precursory or co-eruptive signals. We analyze InSAR time series spanning August 2, 2023 to July 22, 2025 to evaluate localized deformation at Biscuit Basin and broader regional patterns. Cumulative results reveal a persistent center-to-northwest uplift trend in the study area that does not spatially coincide with the Biscuit Basin vent. Comparison of deformation immediately before and after the explosion shows no significant displacement at Biscuit Basin, with line-of-sight changes limited to approximately 0.5 cm under reduced deformation bounds, indicating that the explosion was not accompanied by detectable InSAR-scale ground motion. Time-series analysis indicates subtle regional uplift prior to the explosion, followed by a markedly increased and more spatially extensive uplift rate afterward. Post-explosion deformation is temporally variable, with uplift rates increasing, decreasing, and then increasing again through the remainder of the monitoring period. These observations suggest that InSAR is insensitive to highly localized hydrothermal activity at Biscuit Basin but effective for capturing broader deformation associated with volcanic or magmatic processes. We interpret the pre-explosion signal as the waning phase of regional inflation, with the explosion coinciding.

## Introduction

Hydrothermal and volcanic systems pose a unique monitoring challenge: they are spatially complex, temporally variable, and capable of producing hazardous events with little to no obvious surface warning, without the use of intrusive monitoring approaches. Unlike magmatic eruptions, hydrothermal explosions can occur at shallow depths, and may not be accompanied by clear seismic precursors. This may be especially true in noisy environments, such as Yellowstone National Park, which is a well-known location with high public exposure. The July 23, 2024 hydrothermal explosion at Biscuit Basin in Yellowstone National Park brought this challenge to the headlights. This event occurred in a heavily visited area, which highlights the critical need for monitoring tools that can detect subtle changes in near surface conditions while remaining scalable, non-invasive, cost-effective, and deployable over long time periods.

Interferometric Synthetic Aperture Radar (InSAR) has become a cornerstone technique for observing ground deformation, previously used for different purposes, like hydrological (Smith 2002), CO<sub>2</sub> storage (Alfehaid and Nuncio, 2025) and for scenarios associated with volcanic processes like (Poland and Zebker, 2022). Satellite-based InSAR offers a distinct advantage over in-situ invasive monitoring: it provides consistent, repeatable, spatially continuous measurements across broad regions without placing personnel or infrastructure in hazardous environments. Sentinel-1, in particular, has transformed deformation monitoring by offering freely available data with a global footprint and revisit times suitable for long-term surveillance. However, while the satellite data itself is open-access, the labor, computational resources, processing expertise, and time investment required to produce reliable InSAR time-series are not trivial.

In this study, we present preliminary Sentinel-1 InSAR time-series products developed for the Biscuit Basin region and its surrounding volcanic environment. Rather than positioning these figures as definitive predictive or diagnostic tools, the Results section that follows is intended to evaluate what level of insight is realistically obtainable from a modestly resourced InSAR monitoring effort, and what that insight is worth in the context of hazard awareness and public safety.

From a hazard mitigation perspective, this cost is exceptionally small to nothing when weighed against the potential consequences of unanticipated hydrothermal activity, which very much include human harm. Even if InSAR does not consistently resolve deformation at the scale of individual geysers or vents, its ability to characterize regional deformation trends, background volcanic inflation or deflation, and post-event recovery behavior provides critical context that is otherwise difficult to obtain. InSAR can function as a regional screening tool—highlighting zones of anomalous deformation that may warrant closer geological, geochemical, or geophysical investigation—without requiring constant invasive presence in dangerous areas.

### Methodology

Interferometric synthetic aperture radar (InSAR) is a remote sensing technique where multiple synthetic aperture radar (SAR) images are used to determine changes in ground surface elevation over time (Bürgmann et al., 2000). In this method, satellites collect radar measurements of specific locations, to which the differences in phase and amplitude are then inverted and unwrapped to determine absolute elevation change (Nuncio, 2025) Figure 1.

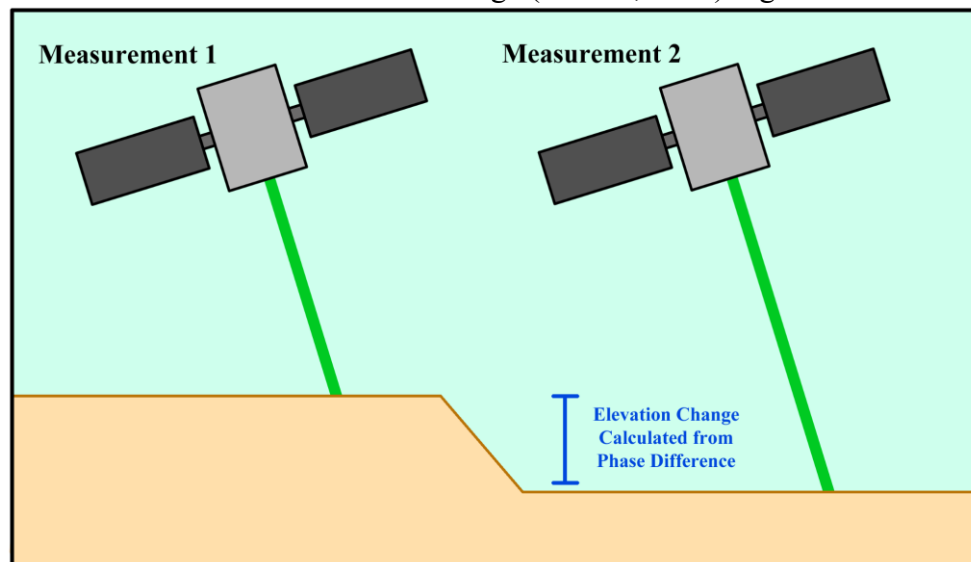


Figure 1: Schematic diagram illustrating how satellites measure ground elevation change over time by calculating the phase difference between two separate radar measurements (Nuncio, 2025).

To determine the ground surface elevation change over time, SAR data was loaded into the Alaska Satellite Facility (ASF) OpenSARLab module that integrates the use of the Miami InSAR Time-Series Software (MintPy) as developed by Yunjun et al. (2019) Figure 2. This program further utilizes the ISCE2 software, using default parameters, that spatially geocode and invert the data. Multiple phases of corrections are then applied to the dataset, as to reduce noise

unrelated to the target signal. Deformation velocity is then calculated, as to determine absolute elevation change.

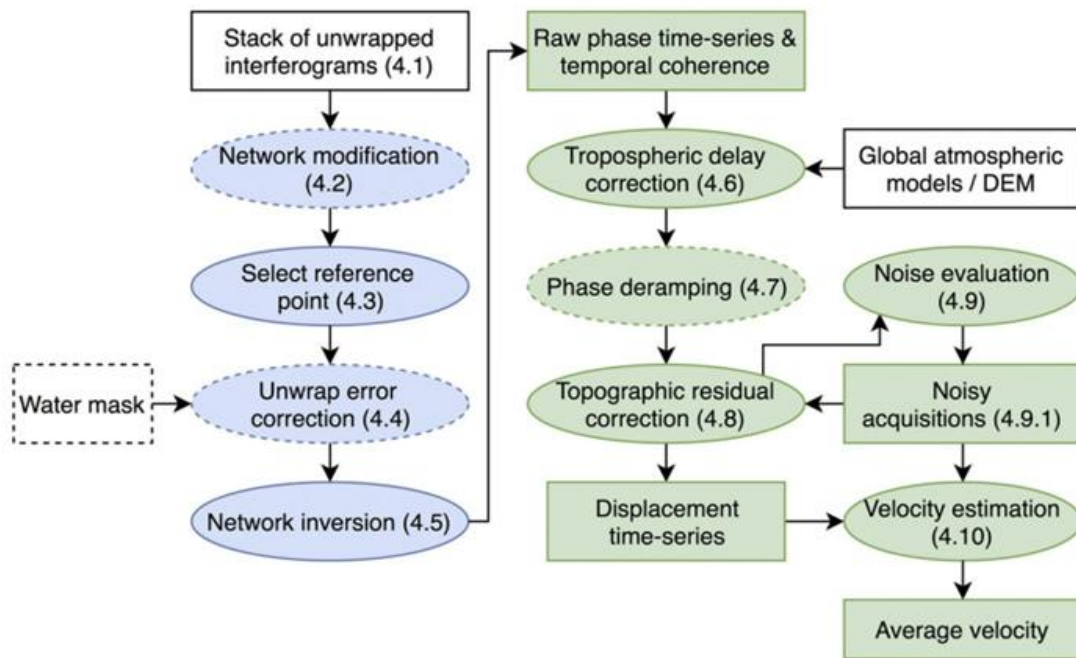


Figure 2: SAR-based workflow in ASF OpenSARLab and MintPy to calculate ground deformation velocity by Yunjun et al. (2019).

In this study, 58 Sentinel-1 SAR images covering the Biscuit Basin area and surrounding portions of Yellowstone National Park were acquired from the ASF Vertex portal. The dataset consists of unwrapped interferometric SAR scenes collected in interferometric wide (IW) swath mode, providing consistent spatial coverage of the study area. Sentinel-1 acquisitions used in this study have revisit intervals of approximately 6–12 days, enabling construction of deformation time-series over multi-year periods.

The analysis period spans August 2, 2023 to July 22, 2025, encompassing the interval immediately preceding and following the July 23, 2024 hydrothermal explosion at Biscuit Basin. All SAR scenes intersecting the defined area of interest were imported into OpenSARLab for processing and time-series generation.

InSAR time-series processing was conducted using the OpenSARLab workflow, which integrates the Miami InSAR Time-Series software package (MintPy). Unwrapped interferograms were inverted to estimate temporal line-of-sight (LOS) displacement, with standard corrections applied for orbital errors, topographic phase contributions, and atmospheric and noise-related artifacts. Interferogram generation and preprocessing were performed using ISCE2 within OpenSARLab. Default processing parameters were employed, with a multilooking factor of  $10 \times 2$  applied to improve signal-to-noise ratios while maintaining adequate spatial resolution for regional deformation analysis.

To facilitate visualization of low-magnitude deformation signals, selected time-series and cumulative deformation products were displayed using deformation bounds of  $\pm 2$  cm, while

broader bounds were applied where appropriate to assess regional deformation patterns. All time-series outputs were referenced to a stable area within the study region to minimize long-wavelength artifacts. The resulting deformation products form the basis for subsequent analysis of spatial and temporal ground displacement within the Biscuit Basin region.

## Results and Discussion

The figures presented in this section serve three primary purposes. First, they demonstrate the type and scale of deformation information that can be extracted from Sentinel-1 data using semi-automated processing workflows. Second, they illustrate the spatial relationship between localized hydrothermal activity and broader volcanic deformation patterns. Third, they provide a foundation for discussing whether extended temporal coverage—despite increased processing demands—may meaningfully enhance interpretability and hazard relevance. By framing these results in terms of cost, scalability, and human safety, this study aims to contribute not only to scientific understanding, but also to practical discussions about how limited resources can be allocated to maximize risk reduction in active volcanic and hydrothermal systems.

### InSAR Observations and Spatial Deformation Patterns

Interferometric Synthetic Aperture Radar (InSAR) time-series analysis spanning 2 August 2023 to 22 July 2025 reveals spatially heterogeneous deformation across the Biscuit Basin region and its surroundings. Cumulative line-of-sight deformation indicates a pronounced uplift signal ( $> +10$  cm) concentrated in a center-to-northwest-trending zone within the study area (Figure 3). This deformation pattern is not located around the Biscuit Basin geyser itself and persists throughout much of the monitoring period.

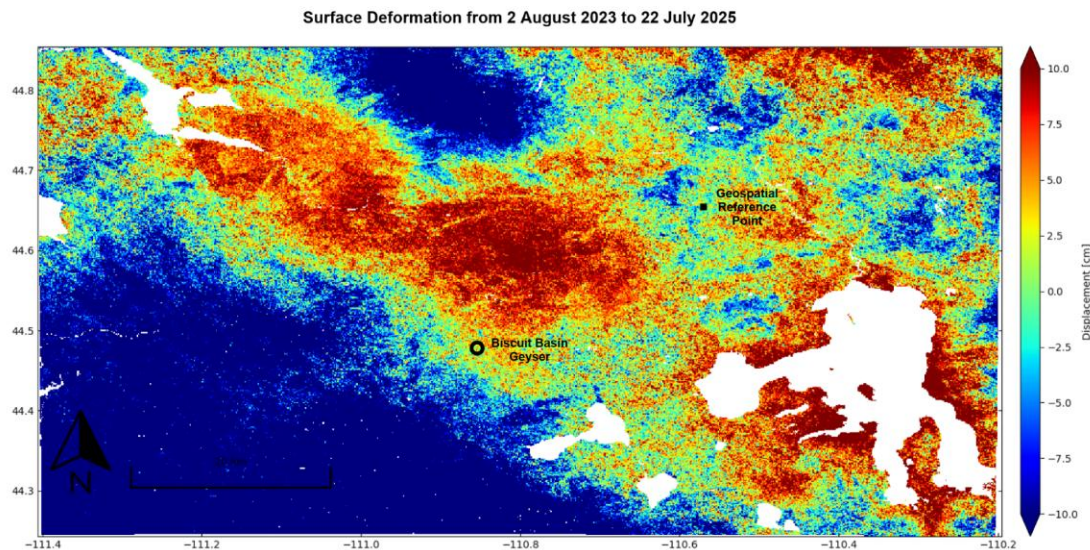


Figure 3: Cumulative Sentinel-1 LOS deformation (2023–2025) showing high uplift rates ( $> +10$  cm) throughout the central-to-northwest portion of the study area.

### Deformation Associated With the 23 July 2024 Hydrothermal Explosion

Comparison of deformation immediately before and after the 23 July 2024 hydrothermal explosion (measured between 15 July 2024 to 27 July 2024) shows no resolvable co-explosive or precursory deformation localized at Biscuit Basin (Figure 4). Only minimal uplift is observed at the geyser location, with a maximum amplitude of approximately +0.5 cm. These observations indicate that the explosion was not associated with detectable localized surface deformation at the geyser scale.

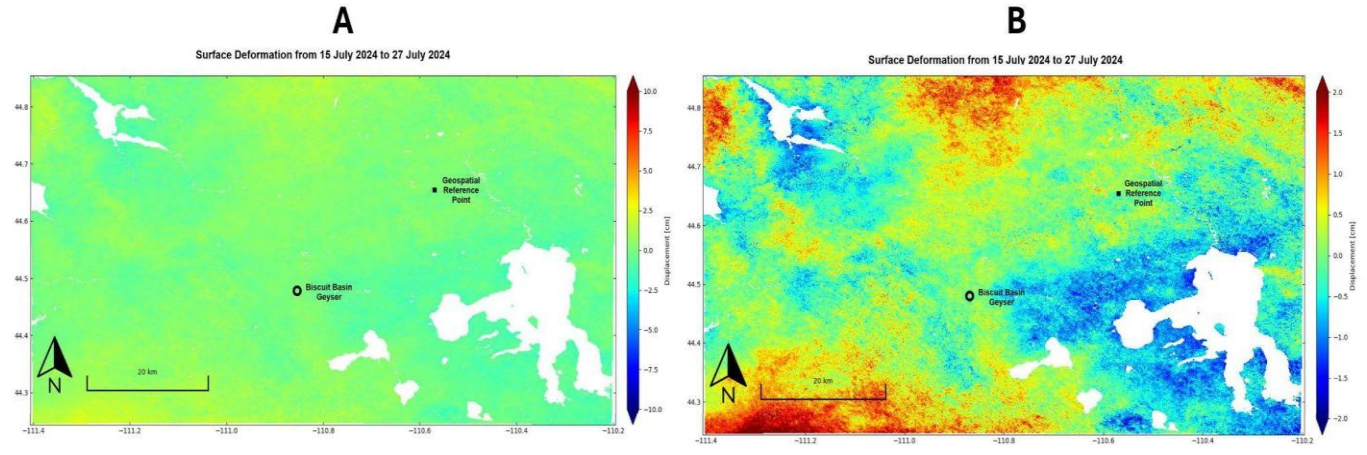


Figure 4: Pre- & post-explosion LOS deformation at Biscuit Basin showing no detectable displacement ( $\leq 0.5$  cm).

### Pre- and Post-Explosion Deformation Evolution

Deformation prior to the explosion (evaluated from 2 August 2023 to 15 July 2024) exhibits subtle, low-displacement uplift ( $\sim +5$  cm) focused toward the central portion of the study area (Figure 5A). In contrast, deformation following the explosion (evaluated from 27 July 2024 to 10 July 2025) is more spatially extensive and exhibits greater uplift magnitudes, with the center-to-northwest trend becoming more distinct ( $> +10$  cm) (Figure 5B).

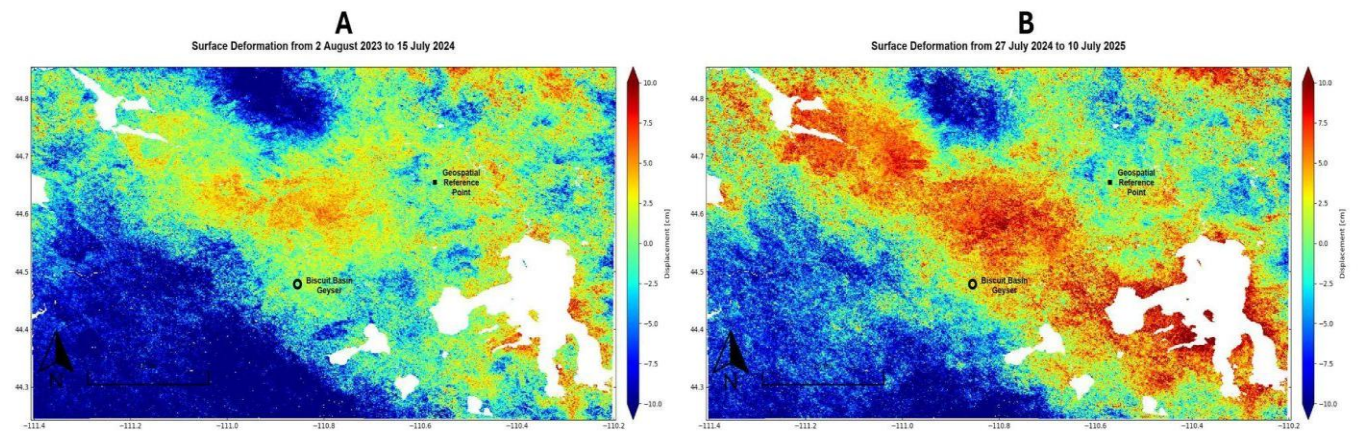


Figure 5: LOS deformation before (A) and after (B) the explosion showing increased post-event regional uplift.

Short-term post-explosion deformation, evaluated following the event from 31 October 2024 to 18 December 2024, shows the same spatial pattern but with low overall amplitudes ( $\sim +3$  cm) (Figure 6). Overall, pre-explosion deformation is characterized by weak, localized uplift, whereas post-explosion deformation is larger and more widespread, suggesting a change in the dominant deformation regime at the regional scale.

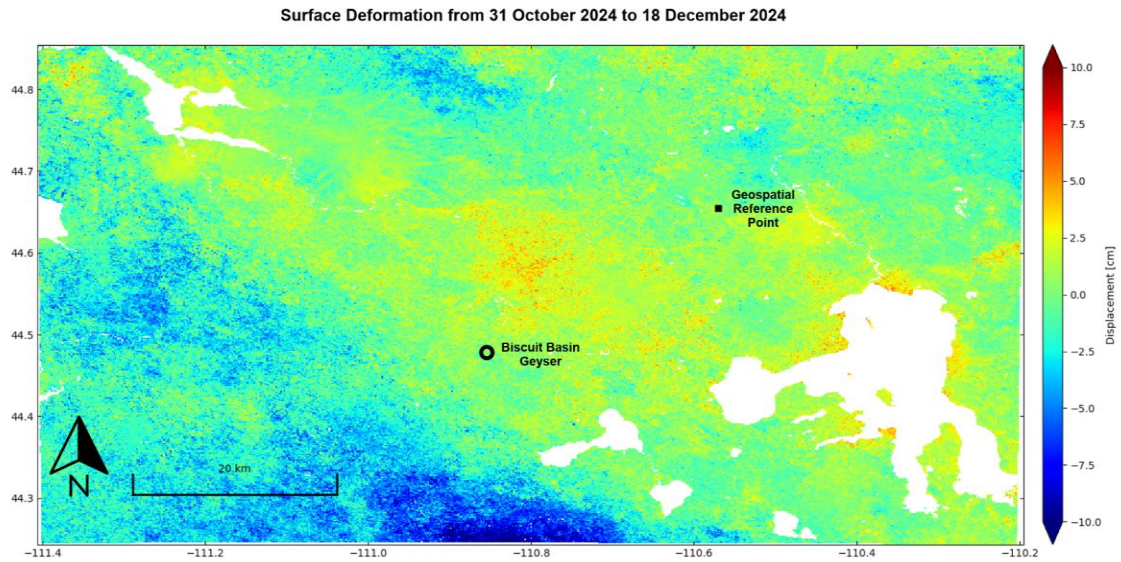


Figure 6. Post-explosion LOS deformation showing low-magnitude regional uplift.

### Post-Explosion Time-Series Behavior

Analysis of post-explosion time-series evolution demonstrates a non-linear uplift progression (ranging from +2 cm to  $> +10$  cm) within the center-to-northwest sector (Figure 7 A-E). Uplift rates increase shortly after the explosion, decrease, and then increase again toward the end of the observation period. This pattern persists through July 2025 and dominates the regional deformation signal.

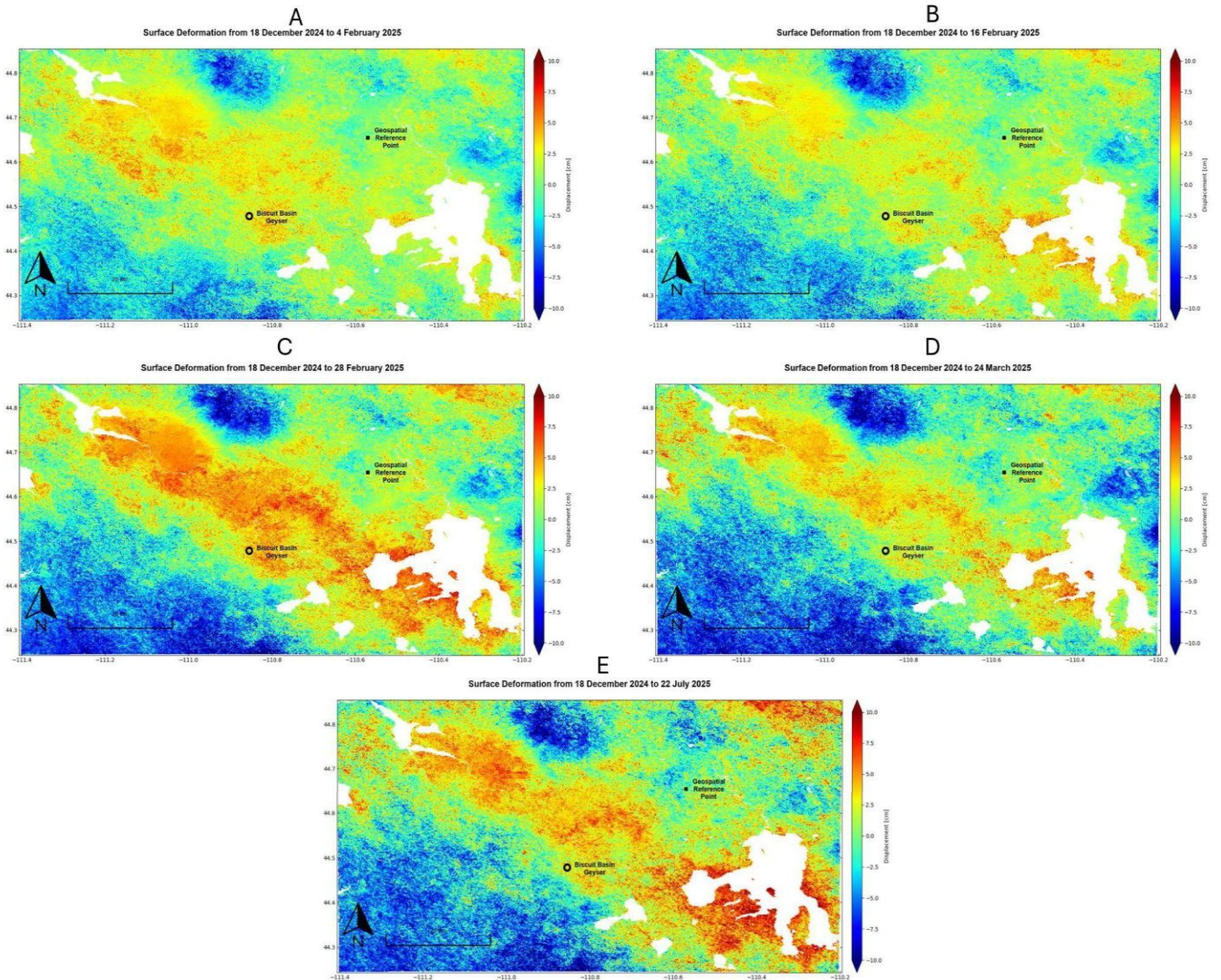


Figure 7: Post-explosion LOS time series showing variable uplift rates.

### Implications for Hydrothermal Explosion Processes

The low amount of displacement of deformation at Biscuit Basin before, during, and immediately after the explosion suggests that the event was driven by near-surface hydrothermal processes rather than by direct magmatic intrusion or pressurization. Hydrothermal explosions at Yellowstone are widely understood to result from rapid flashing of pressurized water to steam within shallow reservoirs (<100–200 m depth), often triggered by changes in permeability, sealing of hydrothermal conduits, or sudden pressure release along pre-existing fractures. The observed maximum uplift of ~0.5 cm at Biscuit Basin further indicates that any pressurization prior to the explosion was minor, localized, and likely dissipated rapidly during the event. This reinforces the conclusion that InSAR is not well suited for monitoring individual geysers or isolated hydrothermal features at Yellowstone, especially when deformation amplitudes are small and spatially confined. Therefore, we conclude that while InSAR has been effective in

monitoring geyser deformation, it was unable to delineate deformation related to the July 23, 2024 hydrothermal explosion.

### **Regional Uplift and Volcanic System Processes**

In contrast to the localized behavior at Biscuit Basin, the persistent center-to-northwest uplift signal points to deeper, regional-scale processes operating within the Yellowstone volcanic system. Yellowstone is characterized by long-term deformation associated with magma and volatile movement beneath the caldera, with uplift and subsidence episodes occurring on timescales of years to decades (Delgado and Grandin, 2021). The spatial offset between the uplifted region and Biscuit Basin suggests that the observed deformation is unlikely to be directly driven by the shallow hydrothermal system feeding the geyser, and instead may reflect deeper processes within the upper crust, potentially involving magmatic fluids or a magma reservoir beneath Yellowstone Caldera (Duan et al., 2025). The center-to-northwest orientation of uplift may be influenced by pre-existing structural trends or zones of enhanced permeability that localize fluid and magma transport. In this context, the northeastward migration of rhyolitic melt storage and heat input inferred by Bennington et al. (2025) suggests that the observed center-to-northwest uplift pattern is not primarily controlled by the deeper magmatic configuration imaged in that study, and may instead reflect more localized or structurally guided processes.

### **Implications for Monitoring and Hazard Assessment**

These results highlight the importance of scale when interpreting InSAR data at Yellowstone. While InSAR was unable to detect deformation associated with the July 23, 2024 hydrothermal explosion, it remains a powerful tool for detecting broader volcanic deformation that reflects system-wide processes. The lack of a clear precursory InSAR signal at Biscuit Basin underscores the challenge of forecasting hydrothermal explosions using satellite approaches alone and emphasizes the need for on-site non-invasive monitoring methods. Ultimately, surface deformation can be caused by a wide range of factors, and cannot isolate the source of deformation. Thus, additional monitoring approaches should be concurrently employed. Hydrogeophysical approaches are especially well-suited for this environment and include geoelectrical monitoring systems (Smeltz et al., 2022) such as electrical resistivity tomography (ERT) lines or electromagnetic (EM) methods, and even magnetic methods (Biasi et al., 2022), in addition to further utilization of existing seismic stations. Evaluation of these datasets together allows for more-refined determination of the causes of surface deformation.

### **Limitations and Long-Term Context**

Finally, the possibility that the analyzed time window captures only the latter part of a longer inflation cycle suggests that extending the InSAR time series further back in time could provide critical context for interpreting the observed deformation. Long-term InSAR records have proven essential in distinguishing short-term deformation associated with individual events from background volcanic cycles at Yellowstone. If feasible, expansion of the dataset to include earlier years would help clarify whether the pre-explosion uplift represents a declining inflation phase and whether the post-explosion uplift marks the onset of a new deformation episode.

### **Conclusion**

The Biscuit Basin explosion underscores the human dimension of this problem. The event occurred in a setting where visitors, researchers, and park staff routinely operate at close

proximity to an active hydrothermal feature. While no single monitoring technique can eliminate risk, integrating low-cost InSAR surveillance into broader monitoring frameworks has clear potential to reduce human exposure by informing access decisions, guiding field deployments, and contextualizing short-term observations within longer-term deformation patterns.

Importantly, this value exists even when InSAR does not show dramatic precursory signals; knowing where deformation is absent can be just as informative as knowing where it is present.

In summary, the Biscuit Basin explosion appears to be a shallow hydrothermal event superimposed on ongoing regional volcanic deformation. The InSAR observations reinforce the decoupling between localized hydrothermal activity and deeper magmatic processes at Yellowstone, while demonstrating that hydrothermal explosions may occur during periods of broader volcanic system reorganization rather than as isolated phenomena.

Magma movement within the subsurface is in general a potential indicator of increasing volcanic activity that may result in changes in ground elevation. As this movement often results in vertical displacement, InSAR is well suited for measuring these changes. Altogether, our study further substantiates the utility of using remote sensing techniques in volcanic monitoring. However, as ground surface elevation change is a non-unique property, multiple monitoring methods are advised for monitoring, as to better identify true signals of volcanic activity.

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