

Research Paper

Multi-temporal InSAR analysis for assessment of earthquake precursory deformation

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ABSTRACT

Ground deformation is a key parameter in interpreting precursory stress and strain patterns and provides valuable information for seismic studies. Interferometric Synthetic Aperture Radar (InSAR) is a robust technique capable of measuring such deformations with high precision. In this study, we applied Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset InSAR (SBAS-InSAR) techniques to analyze surface deformation patterns prior to the M_W 7.8 Türkiye earthquakes. A total of 40 Sentinel-1 SAR images in ascending mode (path-014) were used, covering the period from January 2022 to May 2023 with a 12-day repeat cycle, both before and after the February 6, 2023, seismic events. The area near the M_W 7.8 earthquake epicenter exhibited deformation rates ranging from -42.9 mm/yr to $+44.3$ mm/yr based on PS-InSAR, while SBAS-InSAR indicated deformation in the range of -58.5 mm/yr to $+47.7$ mm/yr for the same location. The line-of-sight (LOS) deformation from the PS-SBAS merged analysis ranged from -43.4 mm/yr to $+36.0$ mm/yr. The integration of PS-InSAR and SBAS-InSAR provided greater reliability than single-method techniques. Several parameters were analyzed, including the PS-SBAS merged time series, wavelet power spectrum analysis of deformation values near the epicenter, and the first principal component (PC1) of wavelet coefficients, to identify precursory deformation before the earthquake. The PS-SBAS merged time series showed progressive phase decorrelation during the months preceding the event, indicating pre-seismic ground deformation. The wavelet power spectrum of the LOS deformation showed consistently high power from October 2022 to May 2023, suggesting abnormal pre-seismic activity. Furthermore, the monthly rate of change of wavelet PC1 revealed a declining trend prior to the earthquake, followed by an increase afterward. These observations point toward the potential for small-area precursory deformation monitoring using multi-temporal InSAR techniques.

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1. Introduction

Türkiye's geological environment is defined by the active convergence of the Arabian, Anatolian, and Eurasian tectonic plates. This convergence results in the westward escape of the Anatolian plate, which is primarily accommodated by two major strike-slip fault systems: the North Anatolian Fault Zone (NAFZ)

and the East Anatolian Fault Zone (EAFZ) [1,2]. The EAFZ is a large left-lateral strike-slip fault that accommodates much of this tectonic movement, while the Dead Sea Fault Zone (DSFZ) is a comparable structure to the south, running through Lebanon, Syria, and Jordan [3]. The DSFZ and EAFZ are seismically active areas, and high seismic activity has been well-documented in geophysical and geological research [4]. The EAFZ, specifically, is a prominent boundary between the Arabian and Anatolian plates and has witnessed several devastating earthquakes over the centuries [5]. The present research focuses on pre-earthquake deformation specifically around the DSFZ, covering the main shock (M_W 7.8) of the February 6, 2023, earthquakes (Fig. 1). Historical data show that the DSFZ has produced significant earthquakes, such as the

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1759 Lebanon earthquake ($M_W 7.4$), and the 1837 and 1995 Dead Sea earthquakes ($M_W 7.0$) [5]. Likewise, the EAFZ has generated numerous destructive seismic activities, including the 1866 and 1874 earthquakes ($M_W > 7.0$), and more recently, the 2020 Elazığ earthquake ($M_W 6.8$) [6]. Seismic moment tensor solutions have suggested a largely left-lateral strike-slip mechanism along both the EAFZ and DSFZ [7]. The 2023 Türkiye earthquakes occurred on February 6, 2023, at 01:17 UTC ($M_W 7.8$) and 10:24 UTC ($M_W 7.5$), affecting the DSFZ and the Sürgü Fault (approximately 100 km north of the main shock). These earthquakes caused extensive surface rupture, displacement, and widespread structural damage across Türkiye and neighboring regions.

The Pre-earthquake ground deformation pattern may provide valuable information about the impending seismic activity. It is essential to precisely measure and interpret such deformation in order to comprehend earthquake mechanisms, fault processes, and possible precursors. The Interferometric Synthetic Aperture Radar (InSAR) technique has significantly transformed the monitoring of crustal deformation by enabling high-resolution, large area mapping of ground motion prior to, during, and after seismic events [10]. It has proved to be an effective geodetic technique for detecting surface displacements with accuracy on the millimeter

scale [11]. InSAR entails the acquisition of SAR images from airborne or spaceborne platforms at various time periods and the calculation of their phase differences to obtain ground displacement. During the last decades, InSAR techniques have made important progress, allowing the emergence of new methods like Differential InSAR (D-InSAR), Persistent Scatterer InSAR (PS-InSAR), and Small Baseline Subset InSAR (SBAS-InSAR), which are very efficient for studying crustal deformation [12,13]. D-InSAR, which is one of the first InSAR developments, is concerned with separating surface displacement from topography signals through a reference Digital Elevation Model (DEM). This method is well-suited to measure co-seismic and post-seismic deformation patterns in large areas [14]. However, it is prone to temporal and geometric decorrelation, atmospheric artifacts, and noise, and this can reduce its accuracy in some situations [15]. To bypass some of these constraints, PS-InSAR emerged as a time-series InSAR method that relies on stable scatterers, including buildings and outcrops of rock, to measure continuous but small ground displacement over time [12]. The technique is most useful in urban regions and areas with long-term deformation trends and is therefore a necessary tool for the monitoring of earthquake-induced ground deformation. SBAS-InSAR, however, aims to

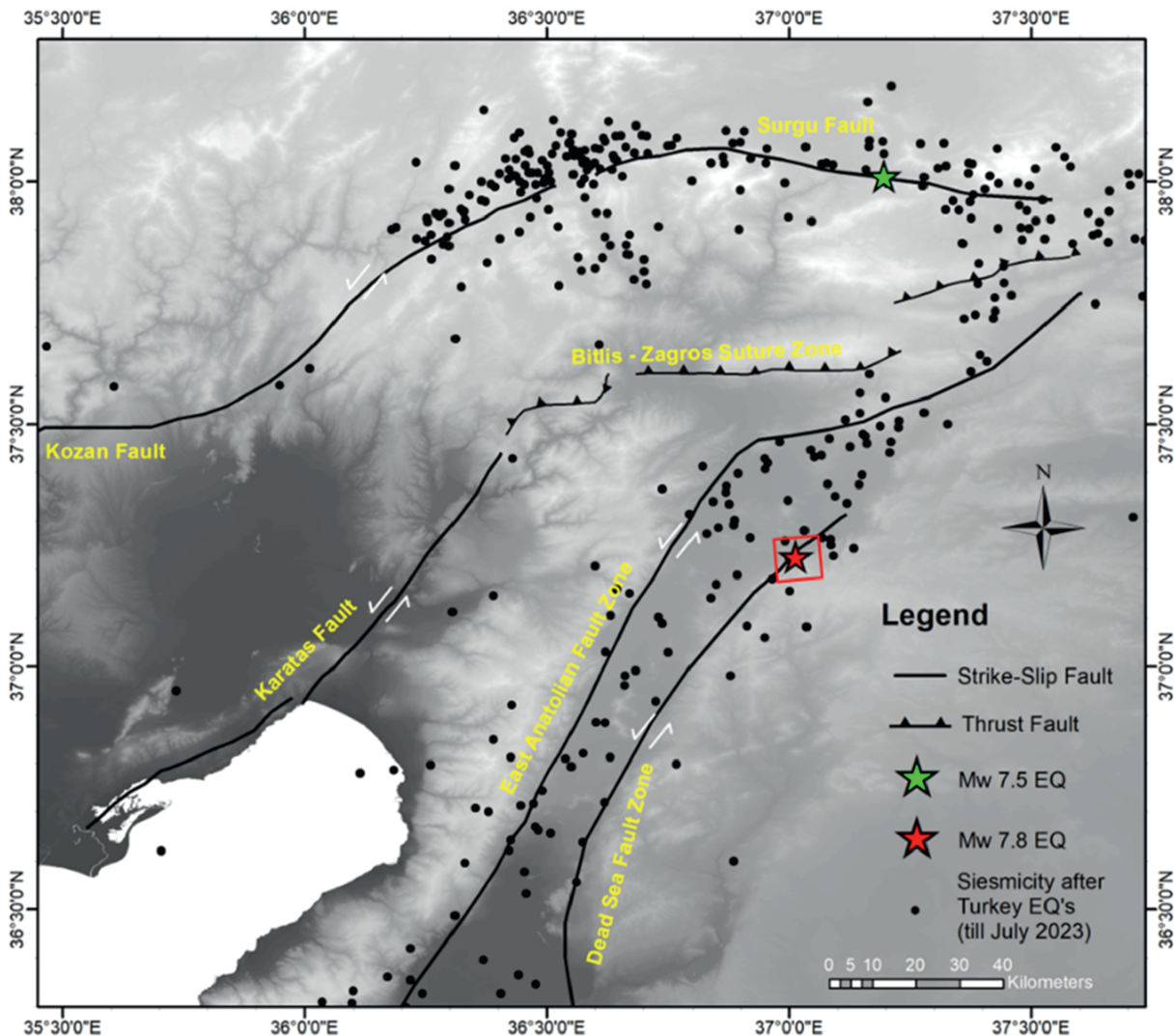


Fig. 1. Study area showing the tectonic discontinuities, epicenters of the February 2023 earthquakes, and recorded aftershocks up to July 2023, based on data from the United States Geological Survey (modified after [8,9]). Red rectangle is the region where PS and SBAS time series analysis were performed.

reduce decorrelation effects through the utilization of several small-baseline interferograms [13]. The capacity of SBAS-InSAR to deliver dense spatial and temporal displacement data makes it a very good option for the identification of seismic potential zones and seismic activity monitoring over time [16,17]. Recent studies have leveraged InSAR's capabilities to analyze the 2023 Türkiye–Syria earthquakes. Li et al. [18] used a spatiotemporal correlation approach to retrieve deformation signatures using multi-track Sentinel-1 data, while Zhao et al. [19] integrated GPS and InSAR to model fault rupture and post-seismic displacement. These studies confirmed the East Anatolian Fault's heterogeneous slip distribution and the complexity of the rupture process. Fattahi and Amelung [20] previously demonstrated the ability of InSAR to resolve strain accumulation along complex fault systems, showing its value in active zones like the DSFZ. More recently, Xu et al. [21] highlighted basement-involved orogeny using geodetic observations, reinforcing the need to consider deep crustal dynamics in surface deformation studies.

Further, Motagh et al. and Moro et al. provided evidence of detectable pre-seismic deformation in the weeks to months preceding large earthquakes, supporting the hypothesis that such patterns may serve as precursors [22,23]. Millevoi et al. [24] proposed AI-driven assimilation models for seismic precursors, suggesting that integration of geodetic and computational approaches can enhance forecasting reliability. Despite these advancements, most precursory studies have emphasized co- or post-seismic analysis, leaving the pre-seismic domain, especially for the DSFZ, relatively underexplored. In this context, wavelet-based time-frequency analysis emerges as a powerful tool for capturing non-stationary deformation signals. In this study, we applied the Morlet wavelet transform [25,26] to the PS-SBAS merged deformation time series near the epicenter. This technique allows for the localization of oscillatory energy at different temporal scales, providing insights into the multi-scale behavior of ground deformation. Notably, our wavelet power spectrum analysis detected persistent high-power anomalies from October 2022 to May 2023, coinciding with the pre- and co-seismic phases. The first principal component analysis (PCA) of wavelet coefficients revealed a declining trend in the months preceding the earthquake, followed by a rebound post-event, suggesting dynamic changes in deformation regimes possibly linked to stress accumulation and release. Such temporal anomalies, when exceeding statistically derived thresholds, can be flagged as potential precursors.

Despite growing access to high-resolution geodetic data and widespread application of InSAR techniques, systematic investigation into pre-seismic ground deformation patterns along the DSFZ remains notably underdeveloped. While numerous studies have successfully used D-InSAR and GPS data to model co-seismic rupture dynamics and post-seismic relaxation in Türkiye and surrounding regions [11,14,18], relatively few have targeted the subtle and potentially transient deformation signals that precede major earthquakes. Recent studies have improved our understanding of rupture behavior by integrating InSAR with GPS observations [19], but these efforts have mostly focused on fault mechanics after rupture. Motagh et al. and Moro et al. provided evidence of pre-seismic anomalies using InSAR, their methods primarily relied on qualitative signal assessment and lacked the advanced time-frequency decomposition required to isolate non-stationary precursory behavior [22,23]. Moreover, their focus was not on the DSFZ, which is a major yet under-monitored fault system with a history of large earthquakes and complex tectonic behavior. This lack of dedicated, high-resolution pre-seismic monitoring represents a critical gap in the current literature, particularly given increasing evidence that slow slip, aseismic fault

creep, and localized stress build-up can be observed days to months before major ruptures.

To address this gap, our study presents a hybrid framework that combines PS-InSAR and SBAS-InSAR techniques with wavelet-based time-frequency analysis and PCA. This approach not only increases spatial and temporal sensitivity but also enables the detection of subtle deformation trends embedded within non-stationary geophysical signals. By applying this methodology to the Sentinel-1 SAR dataset spanning the DSFZ, we identify statistically significant deformation anomalies that occur prior to the $M_W 7.8$ Türkiye earthquake on February 6, 2023. This study is among the first to apply integrated wavelet-PCA techniques to multi-temporal InSAR time series for precursory deformation monitoring in this region. Unlike traditional InSAR studies that emphasize static displacement or long-term strain accumulation, our method isolates temporally localized anomalies potentially indicative of stress accumulation and impending rupture. This contribution not only expands the scientific understanding of short-term crustal dynamics along the DSFZ but also provides a scalable geodetic framework for early precursor detection in other active fault zones.

2. Materials and methods

2.1. Data acquisition

The study utilized C-band Sentinel-1 Synthetic Aperture Radar (SAR) data with a spatial resolution of $5 \text{ m} \times 20 \text{ m}$ to detect ground deformation in the vicinity of the 2023 Türkiye earthquakes. A total of 40 SAR scenes were acquired in ascending mode (Path-014) over the period from January 2022 to May 2023, with a 12-day repeat cycle. Although both ascending and descending tracks are available from Sentinel-1, only the ascending Path-014 scenes were employed in this study due to their higher temporal coherence and more consistent coverage over the epicentral region. In contrast, the descending scenes exhibited substantial decorrelation and intermittent data gaps, limiting their reliability for time-series deformation analysis. The ascending dataset provided sufficient spatial and temporal resolution to detect the relevant ground displacement trends. These scenes encompass both pre- and post-seismic phases relative to the February 6, 2023, seismic events. For topographic phase correction, a 30-m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used, aiding in the mitigation of errors caused by terrain elevation variations [27].

2.2. Data analysis techniques

To quantify and monitor ground deformation before and after the earthquake, we employed a combined InSAR approach that integrates both PS-InSAR and SBAS-InSAR techniques. The Stanford Method for Persistent Scatterers (StaMPS), implemented within the EZ-InSAR MATLAB-based open-source toolbox, was used for processing. This framework supports both PS-InSAR and SBAS-InSAR algorithms by leveraging the Amplitude Dispersion Index (ADI) as a proxy for phase stability and temporal coherence [28,29]. Co-registered SAR data stacks were generated using the Interferometric Synthetic Aperture Radar Scientific Computing Environment (ISCE) module within EZ-InSAR. A total of 39 PS-InSAR interferograms and 134 SBAS-InSAR interferograms were generated (Fig. 2), maintaining a perpendicular baseline threshold within 200 m to ensure coherence [30]. PS pixels were selected based on an ADI of 0.4 in the case of PS-InSAR, while a coherence threshold of 0.6 was applied during SBAS processing [31,32].

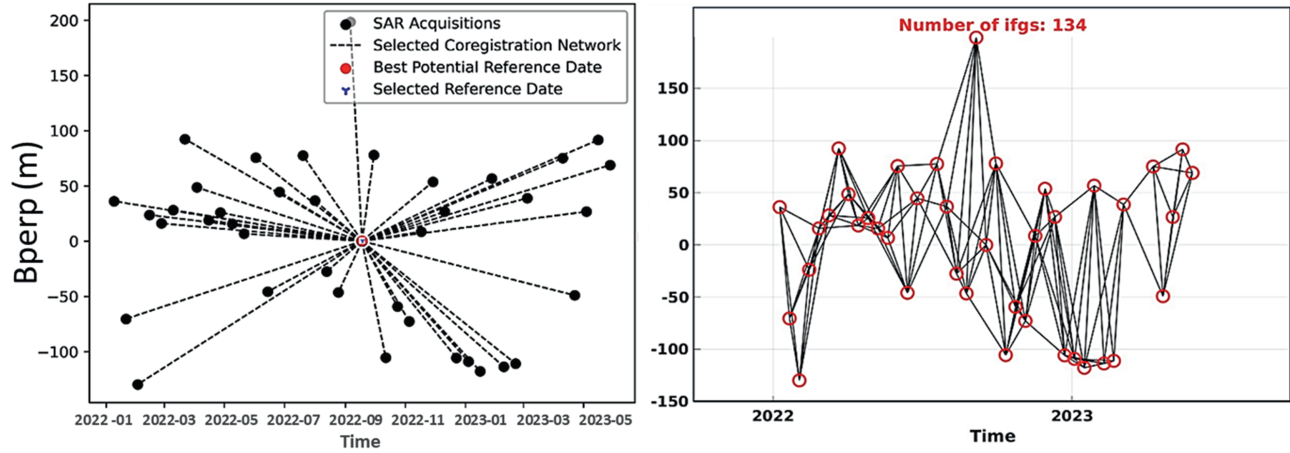


Fig. 2. PS (left) and SBAS (right) network with perpendicular baseline considered in the present analysis.

Atmospheric phase delays were corrected using elevation-phase correlation filtering [33], and the derived velocity fields were deramped using linear models.

To analyze the temporal dynamics of deformation, we applied Morlet wavelet analysis using the Continuous Wavelet Transform (CWT) on the PS-SBAS merged deformation time series. The Morlet wavelet, one of the most widely used mother wavelets for geophysical time-frequency analysis [25], is defined mathematically as:

$$W(a, b) = \int x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (1)$$

$$\psi(t) = \pi^{-\frac{1}{4}} e^{i\omega_0 t} e^{-\frac{t^2}{2}} \quad (2)$$

where ψ is the Morlet wavelet, a is the scale parameter, b is the translation parameter, t is the time, ω_0 is the central frequency, $e^{i\omega_0 t}$ is the complex sinusoid and $e^{-\frac{t^2}{2}}$ is the Gaussian decay envelope.

The Morlet wavelet is particularly effective for analyzing non-stationary signals where frequency components vary over time, such as precursory ground deformation. It offers strong time-frequency localization and is suited to detecting periodic or quasi-periodic signals [26,34]. In this study, the wavelet transform was applied across scales ranging from 1 to 127. From the transformed signal, the wavelet power spectrum was computed as:

$$\text{Power} = |W(a, b)|^2 \quad (3)$$

Further, the average wavelet power across all scales is calculated to detect the anomalies in the power spectrum if the global power exceeds a threshold, which is defined by Eq. (4):

$$\text{Spectrum Power Anomaly} = (\mu + 0.5 \times \sigma) \quad (4)$$

where μ and σ are the global mean and standard deviation of the wavelet power spectrum.

The threshold was set following a variance-based statistical approach commonly used in time-frequency signal anomaly detection. This threshold represents a moderate deviation from the mean, capturing statistically relevant anomalies while avoiding over-sensitivity to noise. The method aligns with prior geophysical studies using wavelet analysis, where thresholds based on $\mu \pm k\sigma$ are used to define significant departures from baseline behavior [35,36]. Although the choice of $k = 0.5$ is semi-empirical, it has been shown to provide a practical balance

between false positives and missed detections in noisy geophysical datasets. To further assess the temporal evolution of deformation behavior, PCA was performed on the wavelet coefficients of the PS-SBAS merged deformation data. This multi-scale PCA (also known as wavelet PCA) applies standard multivariate statistics to the wavelet coefficient matrix, which has dimensions of time $\times$ scale [37,38]. The method is governed by the eigen decomposition, and is given by Eq. (5):

$$\mathbf{C}\mathbf{v} = \lambda\mathbf{v} \quad (5)$$

where $\mathbf{C}$ is the covariance matrix of the PS-SBAS deformation wavelet coefficient, eigen-vector $\mathbf{v}$ is the principal direction, and the eigenvalues λ are the variance in the wavelet coefficient. The wavelet PCA framework is effective for capturing how wavelet energy varies over time and across scales, thus offering a means to detect evolving deformation patterns associated with pre-seismic stress accumulation.

This study combines multi-temporal Sentinel-1 SAR data with PS-SBAS InSAR processing, Morlet-based continuous wavelet analysis, and principal component decomposition to track and interpret subtle ground deformation signals. The processing workflow was executed using EZ-InSAR and custom MATLAB scripts, ensuring high reproducibility and cross-validation of results. This integrative approach provides a scalable framework for future deformation monitoring in other seismically active regions.

3. Results and discussions

3.1. MT-InSAR observations

The application of multi-temporal InSAR (MT-InSAR) stacking techniques effectively minimized atmospheric phase delays and proved highly efficient in capturing urban deformation and post-seismic ground adjustment, as noted in previous studies [28]. In the present study, the PS-InSAR technique produced high-accuracy displacement maps with reduced temporal decorrelation and atmospheric noise interference (Fig. 3(A)). Approximately 30% of the area was excluded due to severe decorrelation, which ultimately enhanced the overall data quality. As reported in earlier research [31], buildings and exposed bedrock yielded the most consistent persistent scatterers, emphasizing the importance of stable targets in urban environments. The analysis revealed localized patterns of both uplift and subsidence near and directly atop the epicentral zone of the $M_W 7.8$ earthquake, with observed deformation ranging

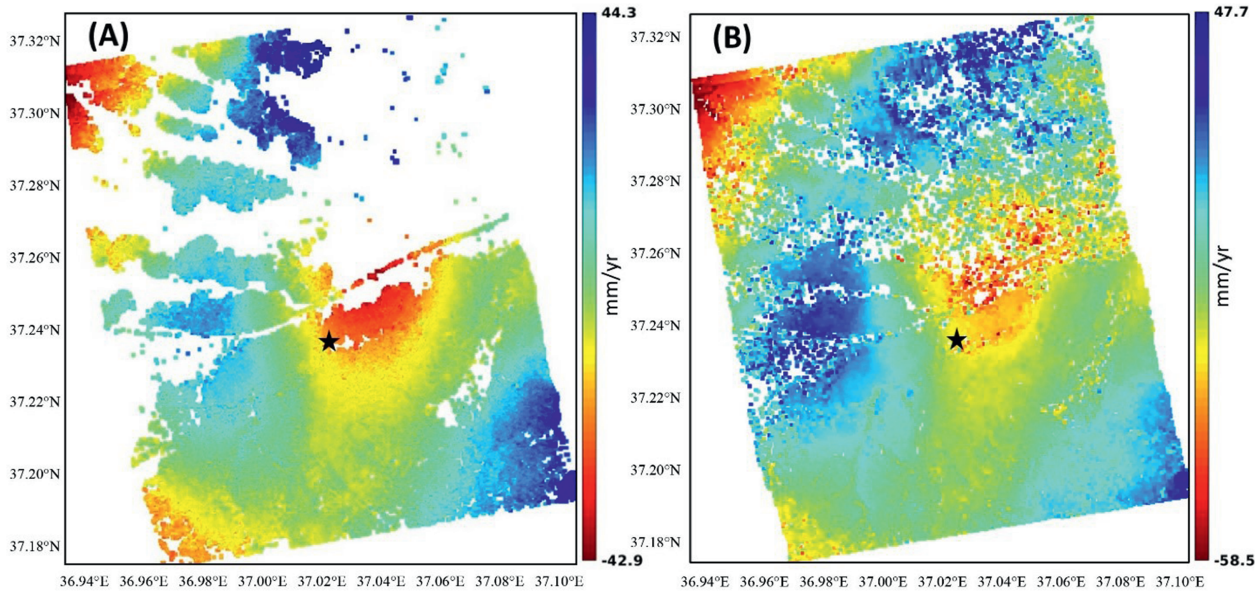


Fig. 3. Time series deformation analysis in the region shown by the red rectangle in Fig. 1 (A) PS-InSAR results; (B) SBAS-InSAR results. The black star represents the epicenter of the M_w 7.8 mainshock.

from -42.9 mm/yr to $+44.3$ mm/yr. Notably, a substantial loss of coherence was observed in PS-InSAR measurements within the immediate epicentral region, likely due to intense ground shaking and surface disruption caused by the earthquake. While the PS-SBAS processing framework includes Atmospheric Phase screening using the Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) model and the spatio-temporal filtering and elevation-phase correlation correction to minimize atmospheric effects [13,39], some residual atmospheric delays may still persist, particularly in areas of low coherence or complex topography. These minor artifacts (as visible in Fig. 3), however, do not align spatially or temporally with the observed tectonic signals. Given the consistency and proximity of the anomalies to the epicentral region, along with their sustained evolution, we interpret the deformation as primarily tectonic in origin.

The SBAS-InSAR analysis, in contrast, revealed a deformation range of -58.5 mm/yr to $+47.7$ mm/yr. These broader ranges underscore the contribution of both persistent and distributed scatterers, with distributed scatterers capturing larger displacements occurring in areas with complex surface dynamics or vegetation. This component is particularly sensitive to deformation occurring off the satellite's LOS, providing additional insight into ground motion geometry. Time-series analysis based on SBAS further highlighted cumulative deformation patterns, reinforcing the hypothesis of progressive stress accumulation leading up to the mainshock (Fig. 3(B)). The method played a key role in the observation of long-term post-seismic relaxation, as earlier documented by Ref. [13]. The capability of SBAS-InSAR to monitor long-term movement is especially useful for investigating transient deformation processes leading to seismic activity [22].

To enhance both spatial coverage and measurement accuracy, a combined PS-SBAS approach was employed (Fig. 4). This integration leverages the strengths of both techniques, the spatial density of SBAS-InSAR, which captures distributed deformation in vegetated or decorrelated areas, and the persistent deformation of PS-InSAR, which offers high precision in urban or stable scatterer zones. The merged deformation product provides an improved delineation between slow, distributed deformation and zones

experiencing more rapid or localized displacement, thereby offering a more robust spatial framework for seismic risk assessment. The LOS deformation in the merged PS-SBAS product ranged from -43.4 mm/yr to $+36.0$ mm/yr. The PS-InSAR and SBAS-InSAR datasets were processed independently and then merged using the "Merge the PS and SBAS points" function within the EZ-InSAR toolbox, based on the StaMPS framework. This method applies spatial filtering and coherence-based redundancy resolution, typically prioritizing PS points where both types are available. In overlapping areas, only one representative point is retained based on signal quality, temporal coherence, and phase stability. This ensures the merged dataset maintains high reliability while avoiding duplication of low-confidence measurement points. As a result, extreme displacement values, particularly those from decorrelated SBAS regions may be excluded, leading to a narrower deformation range. This explains the observed reduction in maximum uplift values in the merged product, which reflects improved robustness rather than data loss. Integration of PS and SBAS techniques has been shown to significantly increase the accuracy and reliability of seismic deformation monitoring, as demonstrated by Ref. [40]. The results presented here confirm that a multi-technique InSAR framework enhances large-scale, localized deformation detection, providing valuable inputs for both scientific understanding and risk mitigation planning.

These deformation results strongly support the notion that stress accumulation and crustal adjustments were active processes in the lead-up to the February 6, 2023, earthquake. The observed pre-seismic deformation trends, especially those detected in the SBAS and PS-SBAS merged products, suggest that the region was undergoing gradual strain localization prior to failure. This aligns with the findings that reported similar pre-seismic surface anomalies in active fault zones [22,41–43]. The ability of SBAS to detect distributed deformation, when coupled with the precision of PS targets, offers a more complete picture of crustal dynamics. The integration of both methods enhances the interpretability of InSAR results in tectonically complex terrains, supporting a growing consensus that high-resolution geodetic observations can play a critical role in advancing our

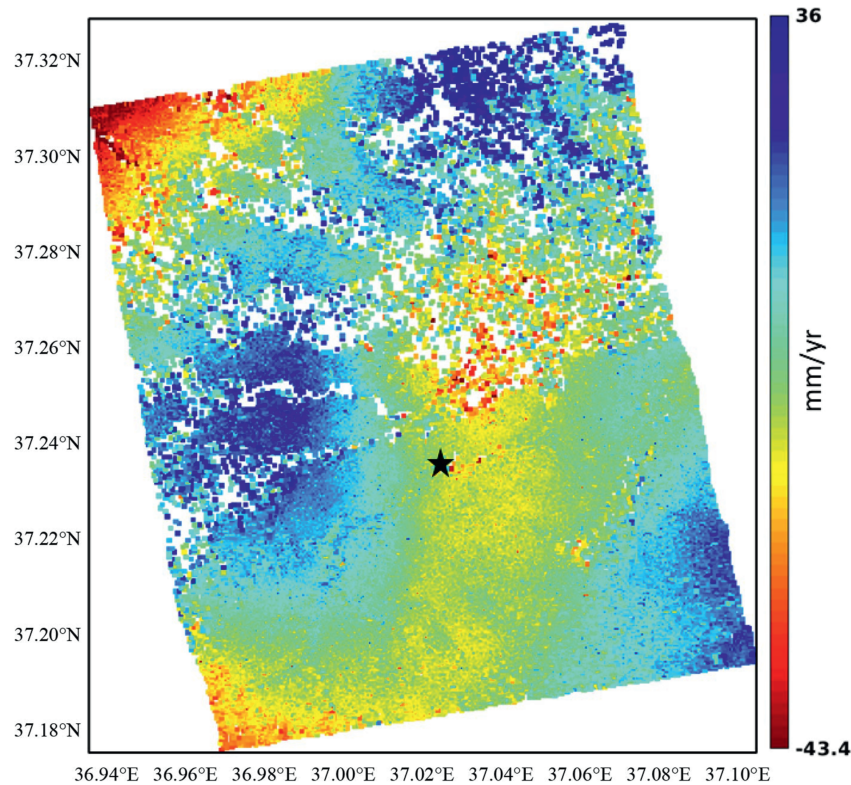


Fig. 4. Deformation time series derived from the combined PS-SBAS approach showing LOS displacement in the region shown by the red rectangle in Fig. 1. The black star denotes the epicenter of the $M_W7.8$ earthquake.

understanding of pre-seismic processes and their potential use in detecting precursory signals.

3.2. Precursory deformation analysis

The multi-temporal InSAR analysis demonstrates significant deformation patterns before and after seismic activity (Fig. 5). While this study focuses on identifying pre-seismic ground deformation, post-earthquake SAR data (up to May 2023) were retained to contextualize pre-event behavior and distinguish long-term trends. This extended temporal coverage allowed for more robust statistical interpretation using wavelet transform and Principal Component Analysis (PCA), enabling clearer separation of persistent pre-seismic anomalies from abrupt co- and post-seismic deformation effects. The analysis identifies a strong rise in phase randomness, or a fall in phase stability, as the earthquake date nears. This effect, especially visible in PS-InSAR and SBAS-InSAR results, indicates a changing deformation field probably related to stress build-up in the crust before seismic rupture. Fig. 5 illustrates this trend through the monthly LOS displacement time series derived from PS, SBAS, and merged datasets. The merged series, in particular, captures a noticeable shift beginning in late 2022, with increasing deviation and instability in the epicentral region, highlighting the temporal alignment between ground deformation and the earthquake preparation phase. It is to be noted that there is no major decline in LOS displacement in the time series, but the spread of deformation/displacement points with time indicates a significant decrease in displacement stability. In other words, randomness increases or phase stability of the deformation points decreases approaching the earthquake date. Further, we analyzed seismic activity that occurred prior to the February 6, 2023, $M_W7.8$ earthquake, within the duration covered

by the InSAR observations (December 1, 2021–February 5, 2023). According to the USGS earthquake catalog, no events were recorded within a 15.5 km radius of the February 6 mainshock during this period. To further evaluate the potential influence of seismicity, we extended the search radius to 30 km. This broader analysis revealed four minor earthquakes, with magnitudes ranging from $M_W4.0$ to $M_W4.3$ (Table 1). However, given their relatively low magnitudes and distances exceeding 15 km from the mainshock location, these events are unlikely to have significantly affected the observed ground deformation patterns. Therefore, the observed decrease in point stability in the deformation time series is attributed primarily to the February 6, 2023 $M_W7.8$ earthquake. The PS-SBAS merged deformation over time suggests progressive phase decorrelation during the months preceding seismic activity, signifying pre-seismic ground deformation. This is consistent with existing research that has reported precursor deformations from using InSAR methods [28,44]. This trend is similar to previous studies that have recognized crustal deformation precursors by radar interferometry [10,13,45]. The resulting pre-seismic phase instability is possibly due to crustal stress perturbations, fault creep, and localized surface deformations, as also previously described in tectonically active areas [46,47].

The wavelet power spectrum of the PS-SBAS merged LOS deformation data (Fig. 6) shows sustained high-power values beginning in October 2022 and continuing through May 2023. The high-power regions, particularly concentrated at larger wavelet scales (lower frequencies), reflect persistent and long-period ground deformation trends. These results suggest that the region experienced a sustained build-up in deformation energy leading up to the mainshock. In contrast, lower wavelet power values before July 2022 indicate relative tectonic stability during that time. This transition from low to high wavelet power marks a

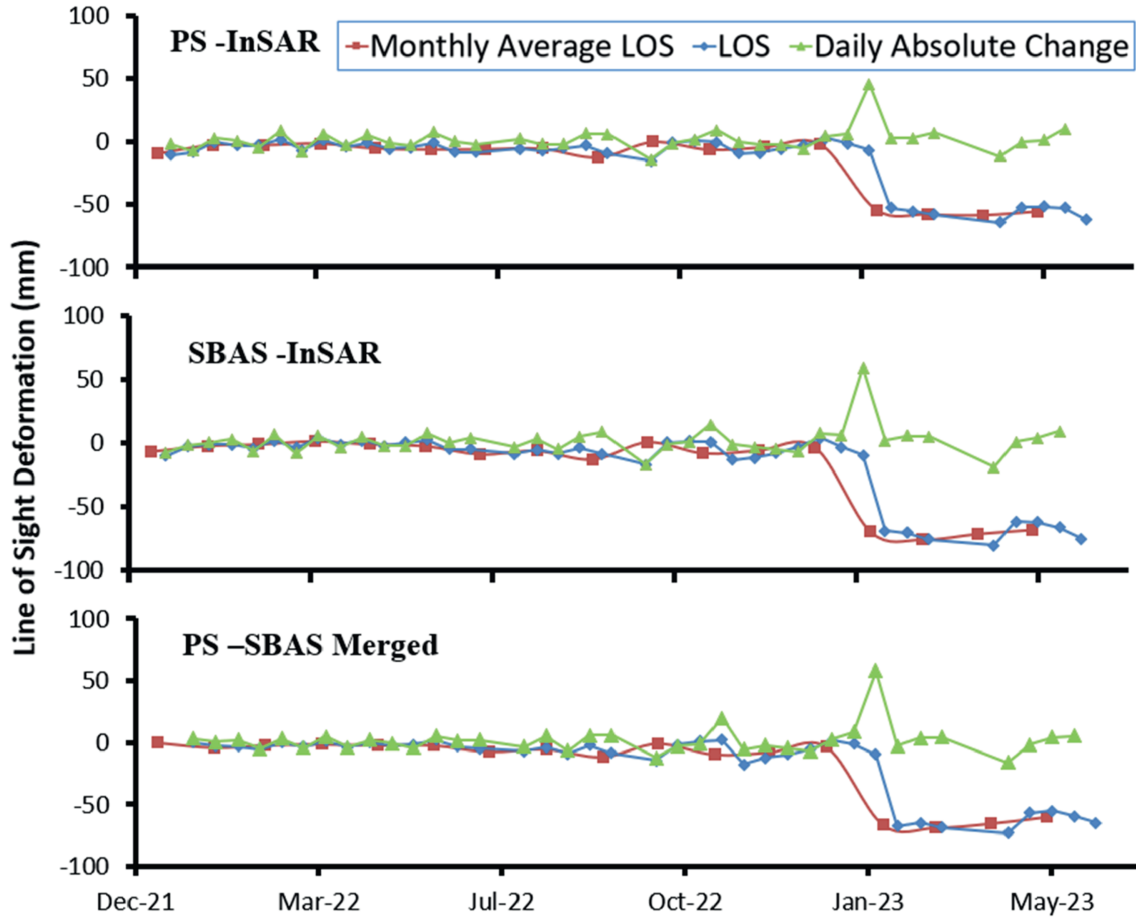


Fig. 5. Time-series InSAR results from PS-InSAR (top), SBAS-InSAR (middle), and PS-SBAS merged (bottom) deformation products. A sharp drop in LOS displacement stability is evident from November 2022 through February 2023, with peak variation in monthly LOS changes coinciding with the earthquake period. The represented time series in all the cases (PS, SBAS and PS-SBAS merged) are from the nearest available deformation point to the earthquake epicenter. The geographic locations of these points are represented by black stars in Figs. 4 and 5.

Table 1
Foreshocks within 30 km from the mainshock epicenter (M_w 7.8, February 6, 2023) during the InSAR observation period (December 1, 2021–February 5, 2023).

Date of occurrence	Latitude (°N)	Longitude (°E)	Depth (km)	M_w	Distance from M_w 7.8 (km)
23-12-2022 17:23	37.1006	37.0917	25	4.1	15.5
26-07-2022 06:11	37.3630	37.0592	10	4.0	45.8
20-10-2022 17:14	37.4183	37.1420	10	4.1	24.2
13-08-2022 03:50	37.4826	37.0408	10	4.2	28.6
20-10-2022 11:35	37.3677	37.2943	10	4.3	30.0

possible turning point in the mechanical behavior of the crust, likely reflecting the onset of pre-seismic strain accumulation. A distinct and localized burst in wavelet energy is observed immediately after the earthquake (February 2023), centered around scales 90–100. While co-seismic deformation is typically abrupt and thus spectrally concentrated at high frequencies (lower scales), the observed post-event power spike at large scales likely reflects a combined effect. Due to the 12-day Sentinel-1 acquisition interval and time-series stacking, the rapid displacement

becomes spectrally broadened. In addition, early post-seismic relaxation, which is gradual by nature, further contributes to power at low frequencies. Therefore, the elevated energy at large scales post-event is interpreted as the result of both immediate co-seismic displacement and the onset of post-seismic adjustments. Fig. 6 visually captures this evolution of energy over time and scale, with the strongest power concentrations emerging at high scales corresponding to long-period deformation signals. The timing and persistence of these low-frequency power anomalies just before the earthquake further support their interpretation as potential precursors.

To isolate periods of abnormal deformation, a wavelet power anomaly threshold ($\text{mean} + 0.5\sigma$) was applied. Time points exceeding this threshold were flagged as anomalies and overlaid on the original LOS time series (Fig. 7(A)). The flagged points align closely with the November 2022 to January 2023 interval, providing further support for the presence of pre-earthquake deformation, and extend into the early post-seismic period, suggesting a gradual return to tectonic equilibrium. Further analysis of the monthly rate of change in the first principal component (PC1) of wavelet coefficients reveals a steady downward trend in PC1 from mid-2022 until February 2023 (Fig. 7(B)). Although 12-day data is theoretically available, there may be missing acquisitions or low coherence in practice. Monthly averaging or aggregation acts as a low-pass filter, removing high-frequency noise and

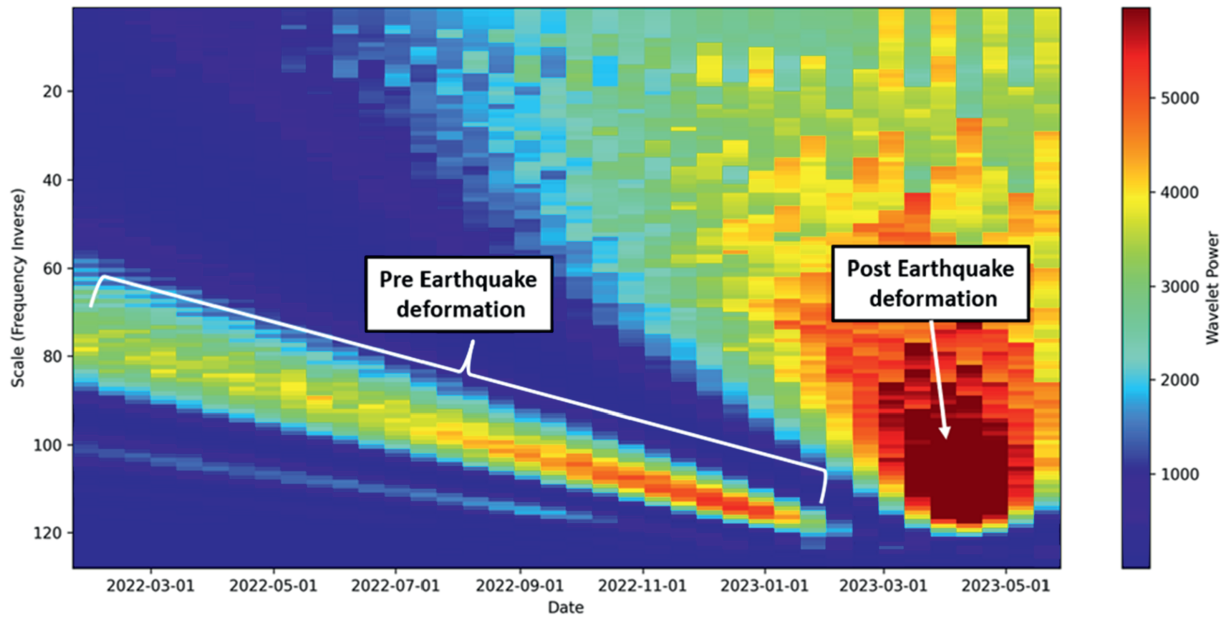


Fig. 6. Wavelet power spectrum of PS-SBAS merged LOS velocity for the duration Jan 2022 to May 2023. Y-axis represents wavelet scales, which are inversely related to frequency. Higher scales = lower frequency (longer-period changes), and lower scales = higher frequency (short-term fluctuations).

allowing PCA to identify meaningful spatial and temporal patterns in the data. Furthermore, many geophysical processes (e.g., slow fault slip in this case) may evolve on monthly or longer timescales, rather than every 12 days. The decline in PC1 rate indicates that the deformation behavior was increasingly deviating from its long-term mean pattern, possibly reflecting a build-up of strain energy or irregular tectonic loading. Wavelet analysis enables the study of time-varying frequency components in non-stationary signals, making it ideal for analyzing geophysical data. PCA is applied to wavelet coefficients rather than raw deformation data to isolate low-frequency, noise-free components. This approach enhances the detection of localized or short-term variations in data, which may serve as a proxy for precursors. PC1 often captures a large share of the total variance (typically between 70% and 90%) in the data. The remaining principal components (PC2, PC3, etc.) explain much less variance and often represent secondary processes or noise. The reversal and rise in PC1 following the earthquake likely represent a return to steady-state deformation or a new post-rupture equilibrium. Such PCA trends are consistent with stress loading and release models observed in other large-magnitude strike-slip fault systems. In addition to PCA-based trends, we also examined the spectral amplitude anomaly derived from the PS-SBAS deformation signal (Fig. 7(C)). The spectral amplitude curve shows a clear and continuous increase from mid-2022 until shortly after the earthquake event, with a peak reached in early 2023. This rising trend suggests progressive accumulation of energy across multiple frequency components prior to rupture, which may reflect heightened crustal instability or intensifying deformation modes. Following the earthquake, a marked decline is observed, consistent with the relaxation and redistribution of stress. Together with the wavelet power anomaly and PCA results, this spectral amplitude evolution further strengthens the interpretation that the region was undergoing a pre-seismic transition marked by measurable surface deformation.

A critical assessment was performed to evaluate whether the observed deformation anomalies could result from non-tectonic sources such as residual atmospheric delays, seasonal signals, or surface processes. To mitigate atmospheric phase artifacts, we employed the PS-SBAS framework, which leverages the amplitude

dispersion index of PS-InSAR with the temporal coherence and spatial density of SBAS-InSAR. The Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) model was deployed in PS-InSAR processing to estimate the Atmospheric Phase Screen (APS). Additionally, elevation-phase correlation filtering was applied during SBAS-InSAR processing to reduce tropospheric effects [13,39]. Seasonal ground deformation, typically driven by hydrological loading or thermal expansion, often follows predictable annual patterns. However, the anomalies identified in this study, particularly those occurring between November 2022 and January 2023 exhibit non-cyclic behavior and do not align with known seasonal variation. To further separate tectonic from environmental signals, we applied the Morlet wavelet transform and PCA, which are well-suited to isolating non-stationary anomalies from periodic background trends [35,36]. The persistence and amplitude of the identified features, along with their reversal following the earthquake, further support their tectonic origin.

Additionally, surface environmental factors such as vegetation growth or freeze-thaw cycles were considered. The DSFZ is situated in a semi-arid zone with limited vegetation, negligible cryospheric activity, and no significant land use or agricultural shifts during the observation period. These environmental constraints reduce the likelihood of non-tectonic surface deformation. The nature and timing of the detected anomalies characterized by gradual growth before the earthquake and sharp transitions afterward, are consistent with previous findings on pre-seismic deformation in InSAR and GNSS data [23,48,49]. While non-tectonic influences cannot be entirely excluded, their impact is considered minimal based on processing safeguards and regional environmental characteristics. The anomalies are therefore interpreted as likely associated with progressive crustal stress accumulation preceding the mainshock.

3.3. Implications for earthquake precursors

The integration of multi-temporal InSAR observations with wavelet and principal component analysis in this study revealed notable spatiotemporal deformation patterns prior to the February 6, 2023, earthquake. These findings, particularly the persistent

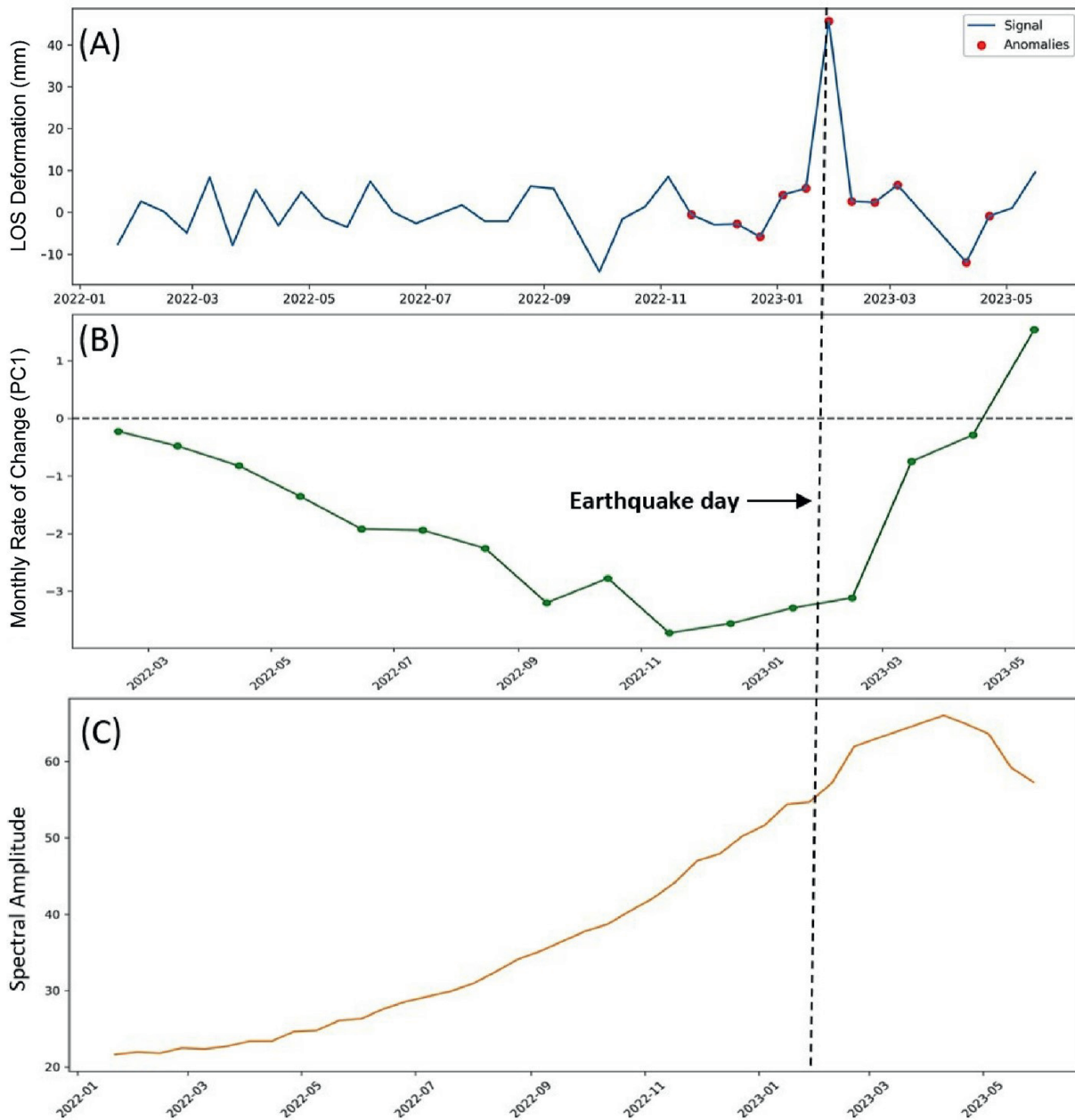


Fig. 7. (A) Deformation anomalies (red dots) overlaid on LOS velocity profile. The strongest anomalies occur shortly before the earthquake. (B) The monthly rate of change in PC1 was derived from wavelet coefficients, which showed a declining trend leading up to the earthquake and a sharp reversal thereafter. (C) Temporal evolution of spectral amplitude anomaly showing a steady increase toward the earthquake day and a sharp decline post-event, indicating elevated pre-seismic energy concentration followed by strain release. The black dashed line marks the earthquake day.

phase instability, LOS displacement anomalies, and long-period wavelet energy build-up in the months leading up to the event, resonate with earlier studies that have documented surface deformation anomalies preceding major earthquakes. For instance, the studies reported similar pre-seismic displacements in fault systems where long-term strain accumulation was followed by short-term kinematic changes [20,47,50]. Likewise, recent studies emphasized the role of slow-slip events and aseismic fault creep as contributors to pre-rupture surface signals identifiable through InSAR and GNSS data [21,51,52].

While this study does not claim to establish a deterministic precursor model, the temporal consistency of multiple independent indicators, specifically wavelet power anomalies and PCA trends, provides converging evidence of gradual tectonic loading.

The use of statistical thresholds to highlight deviations from baseline deformation behavior strengthens the interpretation and offers a replicable framework for retrospective analyses. In contrast to many studies that rely solely on co-seismic or post-seismic deformation analysis, this research extends the scope by focusing on the months preceding rupture and attempts to delineate subtle ground motion patterns that may otherwise be overlooked. The application of wavelet-based methods, which preserve the non-stationary and multi-scale nature of deformation signals, contributes to a more nuanced understanding of earthquake preparation processes. The methodological structure developed in this work, merging PS-SBAS InSAR time series with wavelet transform and multi-scale PCA, can be adapted to other active fault systems. This approach is particularly suitable for

regions with sparse GNSS station coverage, where remote sensing provides a valuable alternative for large-scale deformation monitoring. However, the outcomes also underscore the importance of combining deformation signals with complementary datasets such as seismicity, GNSS-derived strain rates, and atmospheric correction models to filter noise and improve confidence in interpretations. Moving forward, a comparative analysis across multiple seismic events and fault types will be crucial to evaluating the generalizability of such deformation precursors. Longer observation periods and improved data cadence from upcoming missions like NASA-ISRO Synthetic Aperture Radar (NISAR) [53,54] may further enhance the reliability of detecting short-term crustal anomalies. In this context, the results of this study not only contribute to a growing body of evidence suggesting that certain large earthquakes are preceded by measurable surface deformation but also support the advancement of geodetic-based monitoring tools for improved seismic risk assessment.

4. Conclusions

The results of this study emphasize the critical role of pre-seismic ground deformation in understanding earthquake preparation processes. By integrating PS-InSAR and SBAS-InSAR techniques, the analysis benefited from both high temporal coherence and broad spatial coverage, improving the stability and continuity of the deformation signal. This combination allowed for better separation of slow and rapid deformation zones, offering a more comprehensive representation of the crustal behavior surrounding the February 6, 2023, M_w 7.8 earthquake. PS-InSAR observations near the mainshock epicenter showed deformation rates ranging from -42.9 mm/yr to $+44.3$ mm/yr, while SBAS-InSAR captured broader displacement from -58.5 mm/yr to $+47.7$ mm/yr at the same location. The merged PS-SBAS analysis revealed LOS deformation in the range of -43.4 mm/yr to $+36.0$ mm/yr, highlighting the added value of combining both persistent and distributed scatterers.

To support the combination of PS and SBAS approaches in improving deformation reliability in the present study, we note that the PS-SBAS merging process employs coherence-based filtering and spatial redundancy resolution. This method retains only the most stable and high-quality deformation points from both PS and SBAS datasets, while excluding decorrelated or low-confidence pixels. As a result, the merged dataset offers enhanced spatial coverage without compromising signal quality. The integration of both techniques thus improves the robustness of deformation monitoring and offers higher reliability. Multiple indicators pointed to anomalous deformation behavior prior to the earthquake. A distinct rise in phase randomness and a decline in phase stability were observed in the epicentral region in the weeks leading up to the event. This instability is interpreted as a sign of evolving tectonic stress and strain accumulation. Wavelet power spectrum analysis of the PS-SBAS time series showed sustained high-power values between October 2022 and May 2023. Statistically significant anomalies exceeding the global mean plus 0.5 standard deviation were detected between November 2022 and January 2023, extending into the post-seismic recovery period. Additionally, the monthly rate of change in the first principal component (PC1) derived from the wavelet coefficients exhibited a declining trend prior to the earthquake, followed by a marked increase afterward. This pattern suggests deviation from long-term deformation behavior during the pre-seismic phase, and a re-stabilization after strain release, possibly indicating a transition to a new mechanical equilibrium. Further, the temporal evolution of spectral amplitude anomalies showed a steady build-up of energy leading up to the earthquake and a post-event decline,

reinforcing the interpretation of progressive stress concentration and subsequent tectonic relaxation.

These findings support the feasibility of small-area, short-term monitoring of precursory deformation patterns using InSAR-based approaches. To strengthen the interpretability and operational utility of such signals, future research should focus on integrating InSAR with other geodetic techniques such as continuous GNSS, leveling, and strain meter data. Advancements in SAR mission capabilities, particularly higher spatial resolution, shorter revisit intervals, and AI-enhanced processing, are expected to further improve the detection of subtle deformation patterns in active fault systems. Overall, this study reinforces the potential of geodetic remote sensing in seismic investigations and contributes to the growing body of evidence suggesting that large earthquakes may be preceded by measurable ground deformation. While the present results demonstrate promising capabilities for detecting precursory deformation, this work remains exploratory in nature and region-specific to the 2023 Türkiye–Syria earthquake sequence. Broader validation across diverse tectonic environments will be essential to confirm the general applicability of the approach and to refine its potential for operational earthquake precursor monitoring.

CRediT authorship contribution statement

Gopal Sharma: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karan Nayak:** Writing – review & editing, Visualization, Methodology, Investigation. **Prakash Biswakarma:** Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation. **Rekha Bharali Gogoi:** Writing – review & editing, Visualization, Resources. **M.Somorjit Singh:** Supervision, Project administration. **K.K. Sarma:** Project administration. **S.P. Aggarwal:** Project administration.

Data availability statement

The data can be made available upon reasonable request.

Declaration of competing interest

The authors declare that there is no conflicts of interest.

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