International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

IJSRA

(REVIEW ARTICLE)

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Assessment of present-day crustal deformation in the Rio Grande Rift near Socorro, New Mexico, Using Integrated GNSS and InSAR Analysis

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International Journal of Science and Research Archive, 2025, 16(01), 2401–2406

Publication history: Received on 14 June 2025; revised on 24 July 2025; accepted on 28 July 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.16.1.2196

Abstract

The Rio Grande Rift near Socorro, New Mexico is a tectonically active but only moderately instrumented intraplate region where geodetic observations can help constrain present-day crustal and magmatic deformation. This study integrates Global Navigation Satellite System (GNSS) and Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) data to evaluate present-day deformation patterns above the Socorro Magma Body (SMB), one of the largest known mid-crustal magma bodies in continental North America. GNSS time-series analysis from station SC01 was used to estimate station velocity in the IGS14 reference frame, providing a regional kinematic baseline. InSAR interferograms acquired between January and May 2021 were processed to generate unwrapped phase, coherence, and radar line-of-sight (LOS) displacement products for comparison with the GNSS-based regional kinematic reference. The results show a broad, spatially organized LOS uplift signal of up to approximately +4 mm centered over the previously documented SMB uplift region, superimposed on longer-wavelength gradients without clear discrete offsets along mapped rift-bounding faults. Although some spatial variability is present, the interferometric patterns and coherence maps suggest that atmospheric effects and residual orbital signals may contribute to the short-term signal in addition to any magmatically driven contribution. The integrated GNSS–InSAR approach therefore provides a useful deformation baseline for the Socorro region and supports future studies of magmatic intraplating, rift kinematics, and geohazard evaluation in this slowly extending intraplate setting.

Keywords: Crustal Deformation; Socorro Magma Body; Geodetic Monitoring; GNSS; InSAR

1. Introduction

Quantifying present-day crustal deformation is important for understanding how continental rifts accommodate extension and how mid-crustal magmatic systems interact with the overlying brittle crust. The Rio Grande Rift is a classic example of slow intraplate continental extension, and the segment near Socorro, New Mexico is of particular interest because it hosts the Socorro Magma Body (SMB), an extensive sill-like body of magma at mid-crustal depth that has been associated with measurable surface uplift and persistent shallow seismicity. In such settings, even subtle deformation is important because it helps establish whether the magmatic system is inflating, whether extension is localized on specific rift-bounding structures, and whether measurable motion is spatially concentrated above known magmatic features. Satellite geodetic methods such as GNSS and InSAR are well suited to this problem because they can detect small ground-motion signals that are difficult to capture using sparse conventional networks [1]–[3].

Crustal deformation above the SMB has been recognized for decades. Repeated leveling surveys documented an elongated zone of surface uplift centered near Socorro at rates of a few millimeters per year [4], and subsequent InSAR analyses confirmed ongoing uplift of approximately 2–3 mm/yr over the magma body and refined its spatial extent [5],

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[6]. The lateral extent of the SMB has also been mapped independently using reflected seismic phases from local earthquakes [7], while GPS campaigns across the rift indicate that total present-day extension is slow, on the order of a nanostrain per year distributed across a broad region [8]. Despite this rich observational history, the continuously operating GNSS network near Socorro remains sparse relative to the spatial complexity of the rift and the magma body, and the present-day kinematic behavior of specific sub-regions between benchmarks is still incompletely constrained. In this context, satellite geodesy provides a practical way to address that gap: GNSS offers precise point-based measurements of station motion through time, whereas InSAR provides spatially continuous observations of surface displacement in the radar line-of-sight direction using repeated SAR acquisitions over the same area [1]–[3].

Earlier work by Elbarouni [9] explored digital-twin and machine-learning approaches for reservoir monitoring and characterization. The author previously applied a comparable integrated GNSS–InSAR framework to western Libya and to Yellowstone Caldera, Wyoming, providing a methodological precedent for the present analysis. Although the reservoir-focused studies concentrated on seismic interpretation, reservoir characterization, and subsurface data integration rather than crustal deformation, they similarly demonstrated the value of combining complementary datasets and interpretation methods to strengthen geological understanding under uncertainty. This broader perspective supports the present study.

This study integrates GNSS observations from station SC01 with Sentinel-1 InSAR products to evaluate present-day deformation patterns in the Rio Grande Rift near Socorro. Sentinel-1 is a radar imaging mission designed to provide all-weather, day-and-night observations of Earth's surface, making it well suited for interferometric deformation analysis [10]. The objective of this study is not to directly quantify magmatic hazard, but to establish a geodetic baseline, assess whether deformation is detectable in the available observations, and compare point-based GNSS estimates with spatially distributed InSAR measurements. By combining these datasets, the study provides an initial framework for interpreting crustal motion near Socorro and for supporting future magmatic and geohazard investigations in this slowly deforming intraplate rift setting [10], [11].

2. Geological and tectonic setting

The Rio Grande Rift is a north-trending zone of Cenozoic continental extension that stretches from central Colorado through New Mexico into western Texas and northern Mexico. Near Socorro, the rift consists of a series of asymmetric, fault-bounded basins, including the Socorro and La Jencia basins, separated by intrarift horst blocks and flanked by uplifted rift shoulders. Key structural features in the study area include the rift-bounding normal fault systems along the basin margins, intrabasin faults that segment the valley floor, and the Socorro accommodation zone, a region of complex faulting where the polarity of basin asymmetry changes along the axis of the rift.

The dominant crustal-scale feature of the region is the Socorro Magma Body, a thin, sill-like magmatic intrusion inferred at approximately 19 km depth beneath an area of roughly 3,400 square kilometers. The SMB was originally identified from strong reflected seismic phases generated by local earthquakes, and its lateral extent has been progressively refined through seismological analysis [7]. The magma body is spatially associated with the Socorro seismic anomaly, one of the most persistently active zones of shallow seismicity in the southwestern United States, and with a broad, elongated zone of surface uplift documented by leveling and InSAR observations at rates of approximately 2–3 mm/yr [4]–[6]. This uplift is generally interpreted as the surface expression of ongoing inflation or pressurization associated with the magma body and its thermally disturbed surroundings.

Although the Socorro region is monitored more intensively than many other segments of the rift, instrumental coverage remains concentrated at a limited number of GNSS benchmarks and campaign survey lines, leaving substantial areas of the basin interior and rift flanks without continuous point-based measurements. In such settings, strain and displacement signals can be magmatic, tectonic, hydrologic, or a combination of these, and are often spatially concentrated, requiring high-resolution geodetic techniques for reliable detection and separation from atmospheric and orbital noise in the InSAR record. This framework motivates the application of integrated GNSS and InSAR analysis to evaluate present-day crustal motion and establish a quantitative deformation baseline for regional interpretation and future geohazard assessment near Socorro.

3. Data

3.1. GNSS Data

Continuous GNSS observations were obtained from station SC01, located on the New Mexico Institute of Mining and Technology campus in Socorro, New Mexico, within the area of documented SMB-related uplift. Daily position solutions in the east, north, and vertical components, referenced to the IGS14 reference frame, were obtained through UNAVCO/EarthScope [12]. The time series spans several years of continuous operation, providing a stable basis for estimating long-term station velocity. Station SC01 was selected because of its proximity to the center of the historically documented uplift zone and the length and completeness of its observational record.

3.2. InSAR Data

This study uses Sentinel-1 Synthetic Aperture Radar (SAR) imagery for interferometric analysis. Sentinel-1 Single Look Complex (SLC) scenes were obtained through the Alaska Satellite Facility (ASF) and processed using the ASF HyP3 on-demand processing system [13]. The selected interferograms span the January–May 2021 interval on a descending orbital track, covering the Socorro and La Jencia basins, the surrounding rift flanks, and the full mapped extent of the SMB uplift zone. The semi-arid, sparsely vegetated character of the region provides generally favorable conditions for interferometric coherence.

4. Methodology

4.1. GNSS Time-Series Analysis

Daily GNSS position solutions from SC01 were analyzed to estimate long-term motion in the east, north, and vertical components. Outliers and offsets were screened prior to velocity estimation, and linear regression was applied to the filtered position components to estimate secular velocities in the IGS14 frame. Because a single GNSS station cannot resolve the spatial pattern of deformation across the rift or the localized uplift associated with the SMB, the motion of SC01 is treated here as a regional kinematic reference for background plate motion and rift-scale behavior rather than as direct evidence of localized deformation within any specific sub-region.

4.2. InSAR Processing and Displacement Analysis

Sentinel-1 SLC imagery was processed interferometrically to evaluate short-term spatial deformation patterns. Interferometric products used in this study were generated using the ASF HyP3 processing system, with two-dimensional phase unwrapping performed using established network-based algorithms [14]. Additional analysis was carried out using Python-based tools, and the broader processing framework is consistent with MintPy-based time-series approaches described by Yunjun et al. [11].

The main InSAR processing steps included: importing geocoded unwrapped phase rasters; assessing temporal coherence for quality control; converting phase to LOS displacement; constructing displacement time-series stacks; and estimating mean LOS velocity patterns where appropriate. Because broad long-wavelength gradients can also result from atmospheric delay, orbital residuals, and phase-unwrapping uncertainty, the interferometric products were interpreted cautiously and evaluated together with coherence patterns [3], [15], [18], [19].

4.3. GNSS–InSAR Integration

GNSS-derived velocities were compared with InSAR-derived LOS displacement patterns to assess whether the two datasets were broadly consistent in magnitude, spatial character, and geodynamic interpretation. Because the two methods measure different aspects of surface motion, the comparison was qualitative rather than strictly one-to-one. Similar complementary use of GNSS and InSAR has been widely discussed in geodetic deformation studies, including in actively deforming magmatic and low-seismicity settings [16], [17]. The integrated approach therefore uses GNSS as a regional kinematic reference and InSAR as a spatial screening tool for possible magmatically driven deformation patterns. Together, the two datasets provide a first-order deformation baseline for the SMB uplift zone and surrounding rift structures.

5. Results

5.1. GNSS Results from SC01 Station

Continuous GNSS position data from station SC01 were analyzed to estimate long-term motion in the east, north, and vertical components using daily solutions referenced to the IGS14 frame [12]. Linear regression applied to the filtered position components produced the following velocity estimates: an east component of approximately −13.2 mm/yr, a north component of approximately −5.9 mm/yr, and a vertical component of approximately +1.8 mm/yr. The horizontal components correspond to a total horizontal velocity magnitude of about 14.5 mm/yr, directed toward the west-southwest, broadly consistent with stable North American plate kinematics in the IGS14 reference frame. The positive vertical component is small but persistent across the analyzed record and is qualitatively consistent with the station's location within the historically documented SMB uplift zone.

5.2. InSAR Results

The Sentinel-1 interferograms spanning January–May 2021 reveal a broad, spatially organized LOS displacement signal centered north of Socorro, between the towns of Socorro and Bernardo, within the previously documented SMB uplift zone. Peak LOS displacement toward the satellite reaches approximately +4 mm over the analyzed interval, superimposed on longer-wavelength gradients of ±2–3 mm across the full scene. Coherence is generally high across the basin floors and sparsely vegetated rift flanks, with localized decorrelation along the Rio Grande riparian corridor and in agricultural areas near Bosque del Apache. No clear discrete phase offsets are observed along the mapped rift-bounding faults over this short observation interval, suggesting that any fault-localized deformation during the analyzed period is below the detection threshold of the individual interferograms.

5.3. Integrated Interpretation

The GNSS and InSAR results are broadly complementary. Station SC01 provides a stable regional velocity estimate consistent with rigid North American plate motion plus a small positive vertical component, while the InSAR products identify a spatially coherent candidate uplift zone consistent in location and short-term magnitude with the long-documented SMB inflation signal [5], [6]. Taken together, the point-based and spatially distributed observations suggest that the deformation field near Socorro during the analyzed period was dominated by broad, long-wavelength motion with a localized magmatically influenced uplift contribution, rather than by discrete slip on individual rift faults.

6. Discussion

The observation of a spatially concentrated InSAR uplift anomaly co-located with the historically documented SMB uplift zone highlights the value of multi-scale geodetic interpretation in slowly deforming intraplate settings. This finding is broadly consistent with the wider literature on combining point-based and spatially distributed geodetic techniques in magmatically and tectonically active regions [20], [21], and with prior leveling and InSAR studies of the Socorro region specifically [16]–[23].

Uncertainty remains central to interpretation of the present results. In the GNSS dataset, uncertainty is reflected in the visible scatter of the daily solutions and in the sensitivity of the estimated vertical rate to the length and completeness of the analyzed record. In the InSAR dataset, the short four-month observation window means that atmospheric delay, residual orbital ramps, and unwrapping artifacts can each contribute signals of magnitude comparable to the expected deformation over the same interval. Tropospheric variability associated with seasonal moisture changes along the Rio Grande valley is a particular concern, and the long-wavelength gradients observed in the interferograms may partly reflect such effects rather than tectonic or magmatic deformation [3], [15].

However, the current observations do not provide definitive evidence of the rate, depth, or precise source geometry of the localized uplift anomaly, nor do they capture the full multi-decadal behavior documented in longer geodetic records at Socorro. Stronger conclusions would require longer temporal InSAR coverage spanning multiple years, improved atmospheric correction, and additional GNSS stations distributed across the SMB uplift zone and the surrounding rift flanks to better separate regional plate motion, magmatically driven deformation, and non-tectonic interferometric artifacts.

7. Conclusions

This study applied an integrated GNSS–InSAR framework to evaluate present-day crustal deformation in the Rio Grande Rift near Socorro, New Mexico, a slowly extending intraplate rift segment overlying one of the largest known mid-crustal magma bodies in North America. GNSS time-series analysis from station SC01 indicates horizontal velocity components of approximately –13.2 mm/yr in the east direction and –5.9 mm/yr in the north direction, corresponding to a total horizontal velocity magnitude of about 14.5 mm/yr, broadly consistent with stable North American plate kinematics in the IGS14 reference frame, together with a small positive vertical component of approximately +1.8 mm/yr.

Sentinel-1 InSAR analysis provided spatially continuous observations over the January–May 2021 period. The interferograms, unwrapped phase maps, and LOS displacement products reveal a spatially localized uplift anomaly centered within the documented SMB uplift zone, superimposed on broader, long-wavelength gradients. As a result, while the current InSAR dataset identifies a candidate deformation zone consistent with prior geodetic studies of the area, it does not independently provide definitive evidence of the source depth, geometry, or long-term rate of the localized signal.

The combined GNSS–InSAR analysis nevertheless provides an important first-order deformation baseline for the Socorro region. GNSS offers a regional kinematic reference, while InSAR supplies spatial coverage that helps identify candidate zones of magmatically driven deformation and areas of signal variability. Together, the two datasets improve the geodetic characterization of this scientifically significant and dynamically evolving rift segment, and demonstrate both the value and the limitations of integrating GNSS and InSAR in data-limited, slowly deforming intraplate settings.

Future work statement

This study establishes a preliminary geodetic baseline for the Rio Grande Rift near Socorro. Future work should expand the temporal and spatial coverage of the analysis by incorporating longer InSAR time series spanning multiple years and both ascending and descending orbital geometries, additional GNSS stations distributed across the SMB uplift zone, improved atmospheric corrections suited to the seasonal moisture variability of the Rio Grande valley, and more advanced time-series modeling capable of separating magmatically driven deformation from hydrologic loading and non-tectonic interferometric noise. These improvements would help better distinguish true crustal deformation from interferometric artifacts and would provide stronger constraints for future magmatic, rift-kinematic, and geohazard assessment near Socorro.

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