Estimating Ground Surface Vertical Displacement Using DInSAR Interferometry

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Abstract: *This study estimates vertical ground surface displacement caused by the Mw 4.4 earthquake that occurred on May 19, 2024, in Bogd soum, Ovorkhangai Province, central Mongolia. The selected area lies along active segments of the Ikh Bogd fault system, which is associated with the historic 1957 Mw 8.1 Gobi-Altay earthquake. Specifically, deformation patterns were examined along Fault 20 (north) and Fault 21 (south), as defined in the Mongolian Seismic Fault Map. The analysis utilized Level-1 Single Look Complex (SLC) data acquired in Interferometric Wide Swath (IW) mode by the Sentinel-1A satellite. Two acquisitions from May 15, 2024 (pre-event) and June 7, 2024 (post-event) were processed using the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique within the ESA SNAP software environment to estimate vertical displacement. Results from interferometric processing revealed measurable vertical surface movements, with subsidence reaching up to 7.38 cm and uplift up to 4.29 cm. These findings demonstrate the potential of DInSAR for detecting subtle surface deformations induced by moderate-magnitude seismic events. The study contributes to seismic risk assessment in tectonically active regions of Mongolia and supports the use of SAR-based time-series approaches for long-term ground deformation monitoring.*

Keywords: DInSAR, Vertical Displacement, Earthquake, Sentinel-1, Ground Deformation

Introduction

Throughout history, societies have been exposed to natural hazards that have caused considerable human and economic losses. Disasters are defined as hazardous events that exceed the coping capacity of society and result in significant damage (Disaster Risk Management, 2023). Hazards encompass natural or human-induced phenomena with the potential to affect human life, health, property, cultural heritage, and the environment (Disaster Risk Management, 2020).

In seismology, two essential terms are *intensity* and *magnitude*. Intensity measures the strength of shaking and its impact on people, animals, and structures, typically using a scale from I to XII, whereas magnitude is an instrumentally derived measure of energy release on a logarithmic scale from 1 to 9 (Dash, 2025). Earthquakes represent natural geological hazards caused by the sudden release of accumulated energy in the Earth's crust. This process generates seismic waves and often produces aftershocks until the crust stabilizes (Demberel, 2021). The resulting surface deformation includes subsidence, uplift, and both horizontal and vertical displacements. Traditionally, these have been studied through geodetic, geophysical, and geological field surveys (Serjmyadag, 2017). While accurate, such methods are resource-intensive, costly, and weather-dependent.

Advances in remote sensing provide efficient alternatives. Satellite-based monitoring enables continuous observation independent of weather conditions or physical site access (Amarsaikhan, 2019). Remote sensing data are broadly categorized into optical (passive) and radar (active). Optical systems rely on solar illumination and are limited by atmospheric conditions, while radar systems such as Synthetic Aperture Radar (SAR) actively transmit and record backscattered signals, making them capable of day-and-night imaging in all weather conditions. Sentinel-1 SAR, operating in the C-band at 5.405 GHz (5.5 cm wavelength), is particularly effective for monitoring surface deformation (Amarsaikhan, 2023).

The objective of this study is to detect and analyze short-term earthquake-induced surface deformation using Differential Interferometric Synthetic Aperture Radar (DInSAR). Sentinel-1 data were processed with the SNAP 11 software to produce interferograms and deformation maps, enabling rapid and precise assessment of crustal dynamics in the study area.

Rationale of the Study

Mongolia is located in a highly seismically active region of Central Asia and is considered one of the countries with relatively high earthquake risk according to the global seismic hazard map. Historical records show that in the 20th century, 170 earthquakes with a magnitude of 8.0 or greater occurred worldwide, resulting in more than two million fatalities. Among them, four major earthquakes struck within the territory of Mongolia. Notable events include:

- The 1905 Bulnai and Tsetserleg earthquakes (M 8.3)
- The 1931 Mongolian Altai earthquake (M 8.0)
- The 1957 Gobi-Altai (Ikh Bogd) earthquake (M 8.3)
- The 1967 Mogod earthquake (M 7.3)

Since these earthquakes occurred in remote areas with low population density, the resulting damages were relatively minor. However, these fault zones remain active today and are responsible for generating an average of 20,000–30,000 earthquakes annually. Earthquakes in Mongolia are complex seismic events caused by fracturing, subsidence, and displacement in the Earth’s crust, which are manifested as ground shaking and vibrations on the surface.

According to seismic statistics compiled by the Seismological Sector of the Mongolian Academy of Sciences, approximately 60,000 minor tremors are recorded each year in the country, of which earthquakes with a magnitude greater than 5.0 are considered hazardous

(Dash, 2025). The strongest earthquake in Mongolia during the past century was the M 8.1 event on December 4, 1957, which ruptured a 260 km segment of the Ikh Bogd fault (Amgalan & Bayasgalan, 1999). In recent years, seismic activity has been increasing, and certain regions have been experiencing frequent tremors. This highlights the importance of studying and assessing surface deformation following earthquakes to support disaster risk preparedness, post-disaster recovery, and hazard mitigation.

Seismological studies in Mongolia began in the early 1960s, and by then, western regions of the country were already considered relatively well studied (Dash, 2025). In recent years, the availability of satellite radar data has enabled precise and wide-area monitoring of surface deformation. In particular, Differential Interferometric Synthetic Aperture Radar (DInSAR) based on Sentinel-1 data has become a widely used method worldwide to quantify pre- and post-seismic surface displacements and analyze their spatial and temporal patterns.

Therefore, the aim of this study is to determine post-seismic surface deformation in an area of 31,665.5 km² around Bogd soum, which was affected by the 2024 earthquake, using Sentinel-1 data and the DInSAR technique. The findings will contribute to understanding the characteristics and extent of post-seismic deformation and will provide essential information for seismic hazard assessment and damage evaluation.

Research Aim and Objectives

The aim of this study is to detect and analyze the characteristics and spatial distribution of surface deformation caused by the M 4.4 earthquake that occurred on May 19, 2024, in the central region of Mongolia, within Övörkhangai province. The analysis is based on full-frame Sentinel-1 satellite data using the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique.

For this purpose, pre- and post-seismic Single Look Complex (SLC) images were employed to generate interferograms, perform phase unwrapping, and determine both the magnitude and direction of ground displacement. The study further seeks to identify the overall deformation trends across the study area.

To achieve this aim, the following objectives were set:

- Select and prepare pre- and post-seismic Sentinel-1 IW mode full-frame data for processing.

- Conduct interferometric processing across the full-frame dataset according to methodological procedures.
- Generate interferograms, enhance coherence, and apply phase unwrapping to estimate the magnitude of surface displacement.
- Analyze the spatial distribution of displacement to evaluate patterns, direction, characteristics, and extent of ground deformation

Litetura Review

The study of the morphology of lake basins and their relationship with tectonic movements is essential for identifying fault continuations and assessing levels of tectonic activity. For example, research on the Achit and Uureg lake basins compared their position, shape, water lines, and shoreline features with tectonic fault orientations. The findings confirmed that these basins formed within active fault zones, and their geomorphological features are directly controlled by tectonic processes (Altanbold, 2021).

Recent studies indicate that neotectonic activity in Mongolia has intensified, as evidenced by multiple manifestations such as horizontal and vertical displacements, tectonic fissures, and surface uplifts. Investigations of geomorphological units such as mountains, hills, and depressions in western and central Mongolia revealed variations in neotectonic activity across regions. These findings provide a fundamental basis for identifying seismic sources and modeling fault systems (Amgalan, 1999).

Accurate determination of fault position, orientation, depth, and structure requires geophysical methods, particularly geomagnetic anomaly mapping. Using geomagnetic data, researchers mapped tectonic fault zones in Mongolia and correlated them with surface fault structures. Results demonstrated that geomagnetic anomaly patterns are valuable for identifying subsurface continuations of tectonic faults as well as newly activated faults (Batarchuluun, 2023).

The application of high-resolution satellite radar data to detect long-term deformation has become a new direction in seismic research. For instance, Persistent Scatterer Interferometry (PSI) using Sentinel-1 SAR data has been applied to study post-seismic tectonic displacements and surface movements. This approach demonstrated that subsidence, uplift, and lateral shifts can be monitored over regional scales without the need for field surveys (Bayarsaikhan, 2023).

Study Area

The Arts Bogd mountain range, located within Bogd soum of Övörkhangai province, is separated from Baga Bogd Mountain by its eastern valley and overlaps its western end for more than 20 km. The rear slope of the mountains is steep, rocky, and characterized by Gobi desert features. The highest peak is Ikh Bayan Mountain, rising to 2,477 meters above sea level. The front slope is relatively inclined, with multiple branching ridges, including Dulaankhan Bogd (2,094 m), Zost (1,580 m), and on the eastern end, Halzan Khairkhan. Altogether, the Arts Bogd range and its associated ridges extend for about 180 km.

Numerous perennial springs and streams are found in this region, such as Ikh Bulag, Baga Bulag, Bumba, Söög, Turuukhai, Tsagaan Khad, and Baruun and Züün Khöövör on the eastern side, and Avdrantai, Züün and Baruun Yalatai, Gegeet, Yamaan Us, Kharangad, Khöövör, and Mansrui on the western side. Owing to the abundance of these water sources, the Arts Bogd range experiences frequent fog formation and precipitation throughout the four seasons, replenishing the local hydrological system (Tourist Information Center, 2025).

The Baga Bogd Mountains are situated at the boundary of Baruun Bayangol soum in Övörkhangai province and Bogd soum in Bayankhongor province. The highest peak, Myangan Yamaat Mountain, reaches 3,600 meters above sea level, making it the highest point in the region. Located approximately 20 km west of the Arts Bogd range, Baga Bogd features steep, rocky slopes on its rear side, with gentler, branching ridges on the front.

With its scenic landscapes, diverse flora and fauna, Baga Bogd holds ecological, natural, and touristic significance (Tourist Information Center, 2025).

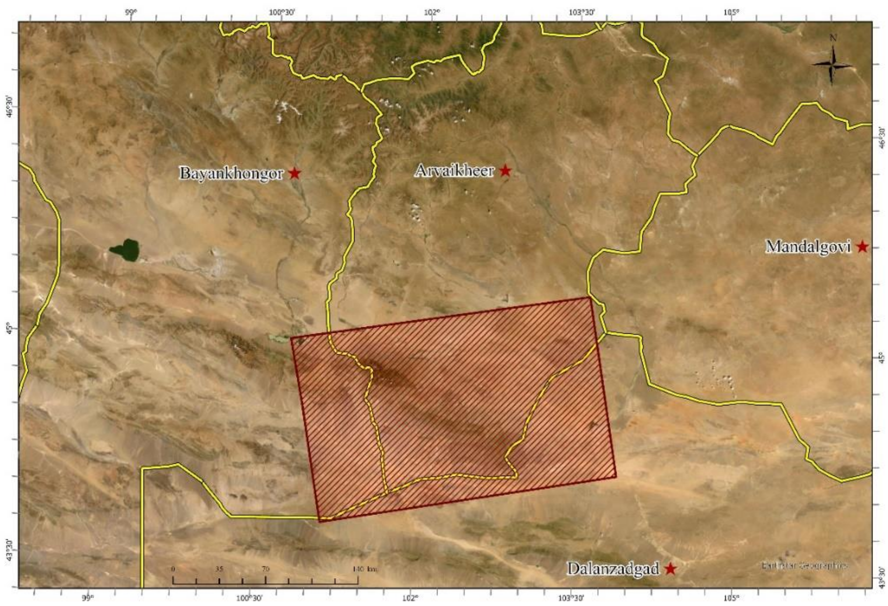


Figure 1: Study area

Significance and Novelty of the Study

Traditionally, post-seismic ground surface displacements have been identified through field-based geological, geophysical, and geodetic measurements. However, with the advancement of active remote sensing, it has become possible to cover large areas in a short period of time and calculate displacements with high precision. This study produced displacement maps based on active remote sensing satellite data, validated through field investigations.

In Mongolia, the conventional approach to determining fault structures, lengths, and orientations has relied heavily on field geological mapping. The novelty of this research lies in utilizing Sentinel-1 satellite Single Look Complex (SLC) data, applying the DInSAR interferometric technique, and performing phase unwrapping and mask generation to produce detailed displacement maps. Importantly, this represents the first direct estimation of post-seismic ground subsidence and uplift in Mongolia using active remote sensing satellite data.

Corrections Made to the Data

In order to ensure data accuracy and reliability of the results during the study, several correction procedures were carried out. First, the Precise Orbit File was applied to improve the orbital path information. To reduce noise in the interferometric phase, Goldstein Phase Filtering was performed. Additionally, to make the wrapped phase information continuous, phase unwrapping was executed using SNAPHU. Finally, Terrain Correction was applied to eliminate spatial distortions and the geocoded imagery was aligned to the WGS84 coordinate system.

Research Materials

In this study, radar data of the Sentinel-1A satellite of the European Space Agency (ESA) in Single Look Complex (SLC) format were used. Pre-earthquake (2024.05.15) and post-earthquake (2024.06.07) images were processed to determine surface displacement using the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique. The processing was carried out with the assistance of the Sentinel-1 Application Platform (SNAP 11) software following the steps described below.

The Sentinel Application Platform (SNAP) is an open-source software suite developed by the European Space Agency (ESA) for the processing and analysis of various types of satellite data. It features a modular structure designed to handle data from Sentinel-1A, Sentinel-1B, Sentinel-1C, as well as other optical and radar missions.

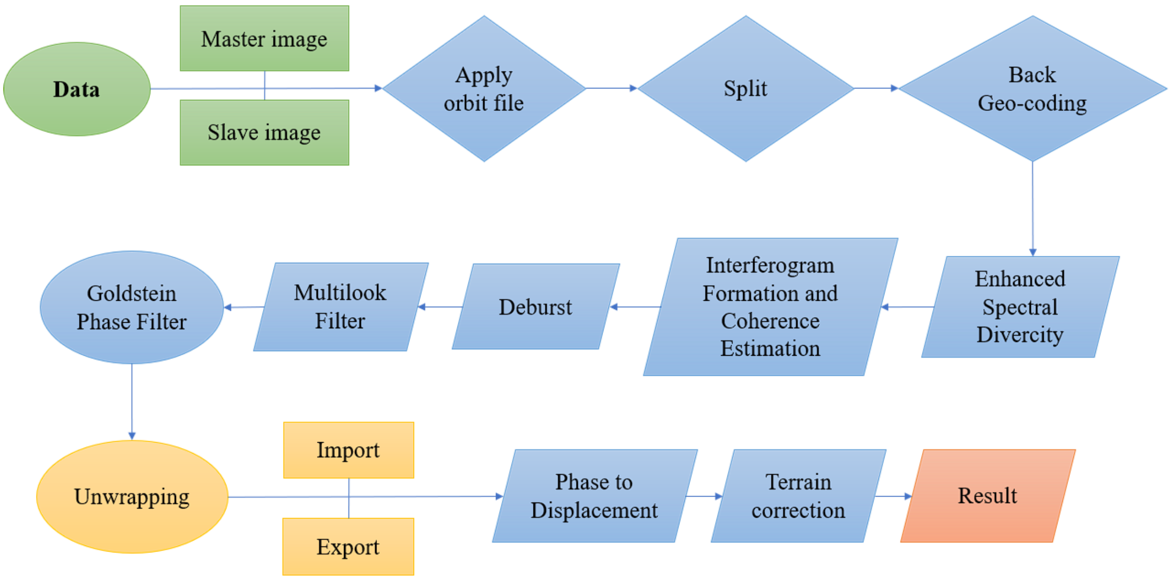
Data Processing

The Copernicus Data Space Ecosystem (CDSE) is a platform established within the framework of the European Union's Copernicus Programme. It provides open, free, and near-real-time access to Earth observation data. The system integrates datasets acquired from Copernicus Sentinel satellites and other sources, delivering comprehensive information on the Earth's surface, oceans, and atmosphere to users.

For this study, the following Sentinel-1A SLC products were used:

- S1A_IW_SLC__1SDV_20240515T110449_20240515T110517_053677_0684F7_1A88.SAFE (Pre-earthquake image, 2024.05.15)
- S1A_IW_SLC__1SDV_20240607T110448_20240607T110516_054377_069D9E_4546.SAFE (Post-earthquake image, 2024.06.07)

Methodology



Scheme 1. Research Methodology Scheme

Results and Discussion

Traditionally, fault structures in Mongolia have been identified through field-based geological mapping. This study is distinctive in deriving vertical displacement directly from Sentinel-1 Single Look Complex (SLC) data using DInSAR interferometry, phase unwrapping, and mask generation. It represents the first attempt in Mongolia to quantify post-seismic ground subsidence and uplift from active radar satellite observations.

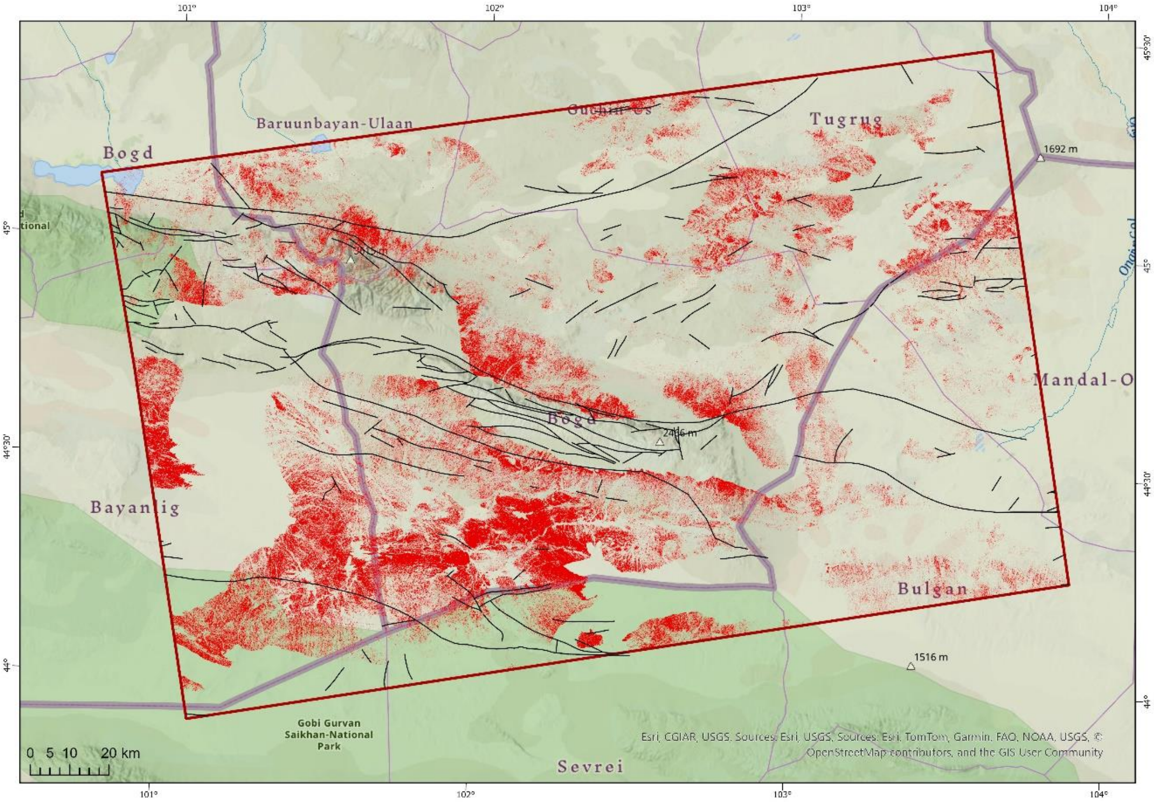


Figure 2. Results of Surface Displacement Analysis

DInSAR enables continuous, wide-area, and high-resolution monitoring of crustal deformation without requiring ground control points or field installations. This makes it particularly suitable for remote and inaccessible regions. In this study, Sentinel-1 radar data acquired before (May 15, 2024) and after (June 7, 2024) the Mw 4.4 earthquake were analyzed, covering an area of 31,665.5 km². Displacement estimates were restricted to regions with coherence ≥0.5 to ensure reliability. A binary mask classified the surface into displacement and non-displacement zones, with deformation pixels highlighted in red.

Results indicate predominant subsidence in the western portion of the study area, especially along the southwestern foothills of Baga Bogd Mountain, while uplift was observed in the central part, notably north of Arts Bogd Mountain. Maximum vertical displacements reached 7.38 cm subsidence and 4.29 cm uplift. Overlaying the deformation map with the 2017 1:500,000 geological fault dataset revealed strong spatial correlation between the observed displacements and mapped fault traces, confirming the tectonic control of deformation.

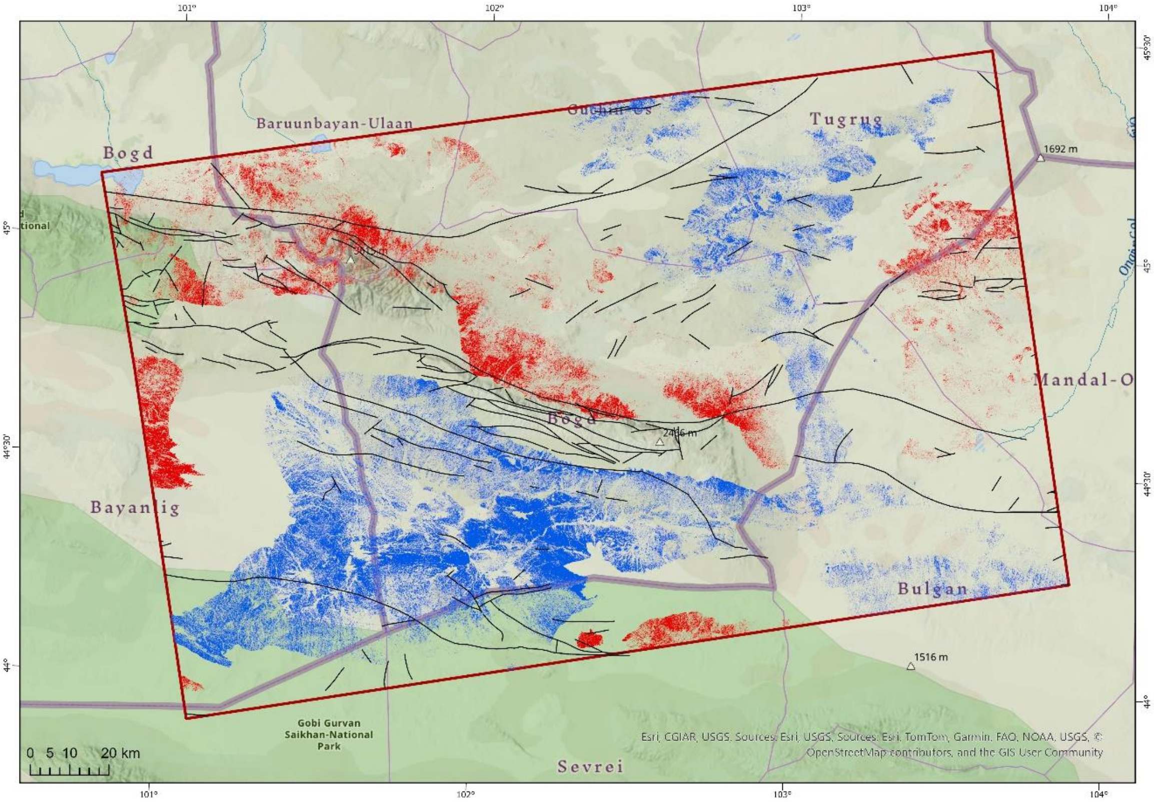


Figure 3. Ground Displacement Results

Conclusion and Recommendation

This study quantified post-seismic ground surface deformation across 31,665.5 km² using Sentinel-1 DInSAR interferometry. Data from May 15 and June 7, 2024, provided a 19-day record of crustal changes following the Mw 4.4 earthquake. Vertical displacements of up to 7.38 cm subsidence and 4.29 cm uplift were detected, with the most significant deformation concentrated along the southwestern foothills of Baga Bogd Mountain and the southeastern slopes of Arts Bogd Mountain.

Interferograms were processed using the Goldstein phase filter, Snaphu phase unwrapping, and coherence thresholding (≥0.5) to minimize noise and ensure accuracy. The consistency of displacement patterns with mapped fault lines further validates the results.

These findings demonstrate that DInSAR is a powerful tool for quantifying earthquake-induced deformation in Mongolia. The approach offers practical applications for seismic hazard assessment, infrastructure risk evaluation, and disaster preparedness. Moreover, the study highlights the importance of developing long-term SAR data archives to support time-series monitoring of seismic deformation processes.

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