DInSAR Analysis of Ground Deformation Induced by the 2023 Al Haouz Earthquake, Morocco

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Abstract

The study investigates the co-seismic ground deformation induced by the Mw 7.2 Al Haouz earthquake that occurred on September 8, 2023, in the Al Haouz region of Morocco. The research employs Differential Interferometric Synthetic Aperture Radar (DInSAR) analysis of Sentinel-1A satellite images acquired before and after the mainshock to map co-seismic deformation patterns and estimate displacement fields. Through this approach, distinct fringe patterns were revealed, indicating significant crustal deformation, with a maximum uplift of approximately 24 cm in the line-of-sight (LOS) direction near the epicenter. Notably, incomplete fringes indicating subsidence were observed in both the northern and southern portions of the fringe lobe, with an associated displacement of approximately 5 cm. The deformation pattern is consistent with a thrust fault mechanism along an ENE-trending reverse fault, forming a horst-pop-up structure. Our findings provide significant insights into the seismogenic fault system and regional tectonics, improving our understanding of earthquake mechanics in this intraplate context and demonstrating the effectiveness of DInSAR in capturing detailed snapshots of co-seismic deformation associated with the devastating event. Additionally, these results have important implications for seismic hazard assessment and disaster risk reduction in Morocco's tectonically active regions.

1. Introduction

On September 8, 2023, an earthquake of around 7.2 on the Richter scale occurred in the Al Haouz region, situated southwest of Marrakech. Due to the extraordinary quake that resulted, around 3000 people lost their lives, countless towns and villages were destroyed, and important roads that connected these impacted areas were blocked. The event's epicenter was situated at coordinates 30.99° N, 8.41° W, with a focal depth of 10.7 kilometers. In contrast to earlier Moroccan earthquakes, this one was unexpected, catastrophic, and occurred within the intraplate context.

Mapping surface deformation associated with earthquakes and estimating co-seismic offsets have been made possible thanks to satellite images. Two predominant technologies in this domain are global navigation satellite systems (GNSS), such as the Global Positioning System (GPS), and satellite technology, namely Interferometric Synthetic Aperture Radar (InSAR) (Larson, 2009; Elliott et al., 2016). Numerous studies have demonstrated that InSAR is a highly effective technique for estimating and monitoring surface deformation caused by a variety of factors (Stramondo et al., 2016; Habib et al., 2017; Carboni et al., 2022). These include tectonic processes such as fault movements and seismic activity, as well as anthropogenic influences, including groundwater over-exploitation, mining activities, and subsidence related to resource extraction. InSAR's ability to provide high-resolution, large-scale measurements of ground deformation over time makes it a valuable tool for both natural hazard assessment and the management of human-induced environmental impacts. By capturing deformation at a millimeter scale, InSAR enables researchers to track subtle changes in the Earth's surface that might otherwise go undetected, offering critical insights into geophysical processes and facilitating the development of mitigation strategies for areas at risk of subsidence or seismic events. This technique's applicability across diverse geophysical and environmental settings underscores its growing importance in earth sciences and disaster management research.

Differential InSAR (DInSAR) is a very effective and consistent method for capturing a snapshot of co-seismic deformations caused by earthquakes. Through the examination of the evolution of SAR phase signals over various acquisitions and the subtraction of topographical relief, information about surface deformation may be derived. Because of this, the DInSAR approach is a helpful tool for identifying topographic variations associated with seismic events.

To estimate the co-seismic deformation resulting from the earthquake and to gain insights into the underlying fault mechanism and seismic activity in the region, a DInSAR analysis was employed by using two SAR pairs from the Sentinel-1A mission with an ascending pass to generate interferograms and measure the phase difference between acquisitions on 3 September and 15 September, and 22 August and 27 September 2023. The co-seismic deformation pattern of

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the earthquake, as indicated by the data analysis, demonstrates a thrust fault mechanism, with the rupture occurring on an ENE-reverse fault.

2. Study Site

2.1 The 2023 Al Haouz Earthquake

With a magnitude of 7.2, the Al Haouz earthquake of 2023, which struck on September 8, 2023, at 22:11:01 GMT, is the greatest in the history of the nation according to seismic stations. The earthquake's epicenter is located in the High Atlas at coordinates 30.99° N, 8.41° W, 72 km southwest of Marrakech, within the rural commune of Ighil. The hypocenter is determined at a depth of 10.7 kilometers. The initial earthquake was followed 20 minutes later by a significant aftershock measuring Mw 4.9. The earthquake resulted in around 3000 deaths, significant destruction, and the collapse of numerous structures, with tremors reported in various regions of Morocco, as well as in southern Spain, southern Portugal, northern Mauritania, and southeastern Algeria.

2.2 Geological Context

The Atlas system, an intracontinental branch of the Alpine orogenic system, is currently considered the result of the Cenozoic inversion of a Mesozoic rift system extending over the North African crust to the south of the Alpine domain, as part of the African-European convergence (Domènech et al., 2015). This convergence is highlighted by GPS data placed in the Rif and Alboran Sea regions. These estimate a NW-SE displacement of around 5 mm/year (Nocquet, 2012). There was also asthenospheric upwelling along an NE-SW axis, which also led to the development of Plio-Quaternary volcanism (Missenard et al., 2006). This gives the causes of the Al Haouz earthquake on 8 September 2023 (Yeck et al., 2023) and that of Agadir on 29 February 1960 (Hatzfeld, 1978).

The Al Haouz earthquake epicenter is located in the Paleozoic massif of the Western High Atlas. The latter consists of two parts: a part to the east, known as the Palaeozoic massif, made up of restricted Meso-Cenozoic remains overlying basement units, and a Meso-Cenozoic fold belt to the west, extending as far as the Agadir-Essaouira marginal basin (Hafid et al., 2006; Benabdellouahed et al., 2017).

The Palaeozoic Massif is divided into three zones: the axial zone in the center and two sub-Atlasic zones, one to the north and one to the south. These zones are separated by longitudinal faults. The axial zone consists of vast outcrops of Precambrian and Palaeozoic units with Triassic deposits preserved in half basins or grabens trapped along the NE to ENE trending Tizi n'Test Fault zone (Qarbous et al., 2008; Domènech et al., 2015). On the other hand, the sub-Atlasic zones expose Palaeozoic outcrops surmounted unconformably by Permian to Cenozoic deposits (Fekkak et al., 2018a).

The Atlasic system has been structured by a series of major accidents, such as the South Atlasic Fault, the North Atlasic Fault, and the Tizi-N-Test Fault (Sébrier et al., 2006; Onana et al., 2011). These faults have a major ENE-WSW to NE-SW direction with NNE-SSW bifurcations (Figure 1). These accidents contributed during the Cambrian rifting (Piqué, 2003; Pouclet et al., 2008). Some were reactivated during the Variscan shortening process (Hoepffner et al., 2005, 2006; Simancas et al., 2005; Michard et al., 2010; Wernert et al., 2016; Chopin et al., 2023). While other accidents contributed to the opening up of the Permo-Triassic basins (Hoepffner et al., 2005, 2006; Saber et al., 2007). And finally comes the Alpine inversion (Ellero et al., 2020 ; Skikra et al., 2021) which obscures older deformation structures and makes it more difficult to understand earlier geodynamic processes.

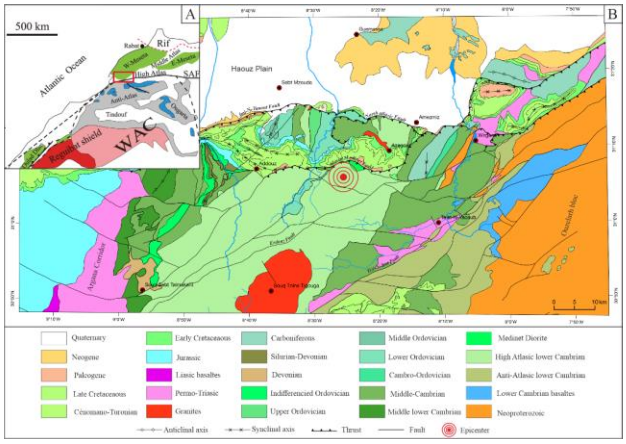

Figure 1. (A) Map showing the position of the Western High Atlas to the north of the Anti-Atlas domain (Adapted from Michard et al., 2008). (B) Structural scheme of the northern flank of the Western High Atlas and the northern sub-atlasic zone (Fekkak et al., 2018b).

3. Materials and Methods

The differential interferometric (DInSAR) analysis of two pairs of SAR satellite images, a pair taken on September 3 and 15, the other pair on August 22 and September 27, 2023, that surround the event was implied by our approach for estimating surface deformation related to the earthquake (Figure 2). SAR images from the Sentinel-1 satellite were obtained via the Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home). We selected two SAR-C images from the available dataset in the SAR images collection, aiming to capture conditions before and after the principal seismic event. The interferograms were derived from the co-registration of the two SAR pairs using the SNAP toolbox version 10.0.0. We utilized an SRTM digital elevation model (DEM) to process the interferogram image, construct a wrapped phase image, and do terrain correction. The quality of the resulting phase image was confirmed using coherence values obtained after the interference image was unwrapped. The phase image was unwrapped using the SNAPHU software before we could obtain a geocoded LOS deformation image of the event.

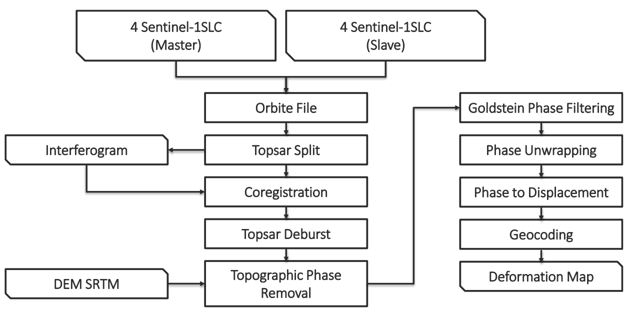

Figure 2. Flowchart showing the DInSAR Method on ground deformation assessment.

4. Results and Discussion

The wrapped interferogram and the associated deformation maps of the Al Haouz earthquake (Figure 3) were generated from an interferometric pair of Sentinel-1 images captured in ascending mode on 3 and 15 September 2023, and 22 August and 27 September 2023, respectively. These data reveal distinct deformation patterns across the affected region. Most notably, the interferometric analysis reveals well-developed fringe lobes in both unwrapped interferograms, indicating significant deformation patterns associated with the earthquake. A prominent fringe lobe is observed on the northwest side of the epicenter, while smaller fringe patterns are evident to the south. Additionally, the fringes on the northern side of the epicenter become narrower, suggesting differential deformation with a higher magnitude of deformation in the northern region, indicative of more significant tectonic movement compared to the south. Notably, these fringes exhibit a linear pattern, suggesting the presence of a fault line intersecting the epicenter and marked by steep terrain changes.

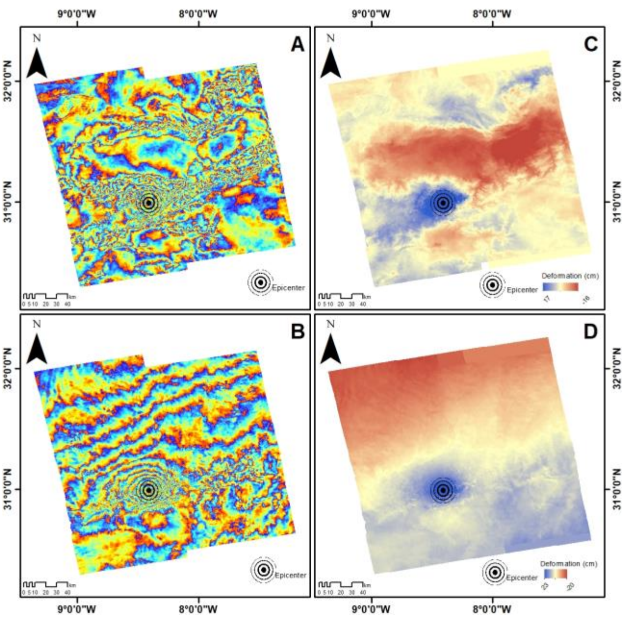

Figure 3. Wrapped interferograms and their corresponding line-of-sight (LOS) deformation maps. (A, C) Image pair: August 22, 2023 – September 27, 2023. (B, D) Image pair: September 3, 2023 – September 15, 2023.

The co-seismic deformation patterns documented through interferometric analysis highlight the predominant role of thrust faulting in shaping the observed ground movements. This encompasses the distinctive uplift and subsidence that characterize the post-seismic terrain. Overlaying the deformation data on delineated fault networks (Figure 4) further supports the conclusion that the regional tectonic framework strongly shapes the spatial distribution of deformation. The North Atlasic and Tizi N’Test faults, in particular, appear to play a pivotal role in driving the seismic activity within the study area, emphasizing their potential as seismogenic sources in this tectonically active zone.

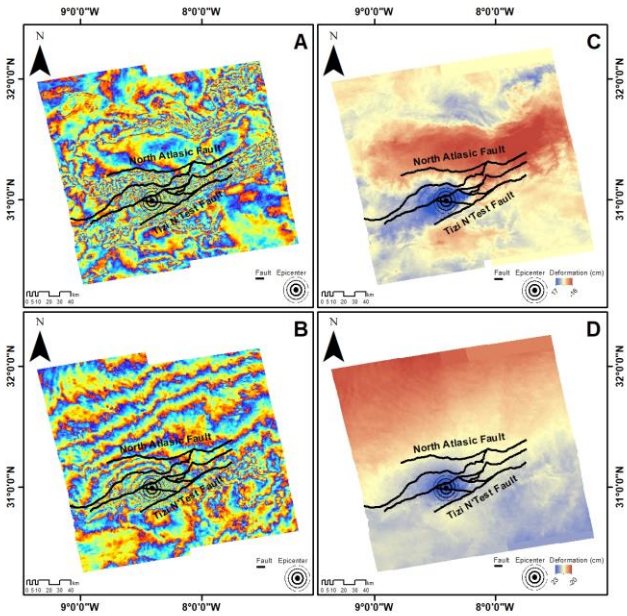

Figure 4. Wrapped interferogram and co-seismic deformation with main tectonic faults reported.

A more detailed analysis of the interferogram and associated deformation patterns indicates that the seismogenic fault responsible for the earthquake is likely oriented in an ENE to NNE direction, aligning with the mapped fault corridor in the region. This corridor exhibits an uplift of up to 24 cm in the line-of-sight (LOS) direction at the epicentral area, marking the maximum displacement during the event. Additionally, subsidence of approximately 5 cm is observed at its northern and southern border regions. These displacement features align with a thrust fault mechanism, where the earthquake rupture occurred along an ENE-trending reverse fault that forms a horst-pop-up structure, highlighting the region’s complex tectonic context.

5. Conclusion

The analysis of the co-seismic deformation associated with the Al Haouz earthquake reveals significant tectonic activity, with a maximum uplift of approximately 25 cm observed near the epicenter. The deformation pattern is consistent with a thrust fault mechanism, where the rupture occurred along an ENE-oriented reverse faults. These findings offer valuable insights into the fault dynamics and seismic processes in the region, contributing to a deeper understanding of earthquake mechanics.

This research holds important implications for seismologists, geologists, and disaster management professionals, as it enhances the understanding of seismic hazards in this tectonically active area. Furthermore, a planned in-depth investigation using Multi-Temporal SAR analysis will provide an opportunity to further explore the relationship between ground deformation and key geophysical factors, such as fault mechanisms, crustal stress changes, and aftershock activity. This expanded research could result in improved models of earthquake behavior, aiding in the prediction and mitigation of seismic risks in the future.

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