

Reconstructing the 2018 Lombok Earthquake Sequence: Insight from An Incident-Angle Corrected InSAR Analysis

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Research Article

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Abstract

The 2018 Lombok earthquake sequence comprised a series of deadly seismic events resulting from the rupture of the Flores Back-Arc Thrust (FBAT), including a foreshock (M 6.4) on July 29, a mainshock (M 6.9) on August 5, and a major aftershock (M 6.9) on August 19. This study quantifies the coseismic surface displacement associated with these three events through Interferometric Synthetic Aperture Radar (InSAR) analysis. Although InSAR enables dense spatial measurement, standard Line-of-Sight (LOS) data are inherently distorted by the satellite's side-looking geometry, particularly in areas with steep topography such as the Rinjani volcanic complex. To address this limitation, an incident-angle correction was applied to derive Corrected Surface Displacement (CSD). The analysis indicates that the July 29 foreshock produced a peak uplift of 13.16 cm at Anyar, the August 5 mainshock resulted in the highest recorded uplift of 62.10 cm at Selengen, and the August 19 aftershock generated a maximum displacement of 40.57 cm at Darakunci. Notably, the foreshock was accompanied by significant subsidence of -13.45 cm at Mt. Rinjani and -10 cm at the Sembalun Region, in sharp contrast to the coastal uplift. This subsidence likely reflects a loss of structural integrity or depressurization within the volcanic edifice and may also indicate compaction of loose volcanic tephra or depressurization of hydrothermal systems triggered by dynamic stress from the foreshock. These findings highlight the necessity of incident-angle corrected InSAR for accurate hazard assessment in complex volcanic back-arc environments

Introduction

Background

The Flores Back-Arc Thrust (FBAT) is situated beneath the Flores Sea, a seismically active region extending from south of Madura Island to north of Flores (Wahyudi et al., 2024). The strain pattern of the FBAT is dominated by compression (Maulida et al., 2024). Lombok Island is located within the FBAT region, particularly in its northern sector. In northern Lombok and Bali, the FBAT slip rate is approximately 14.4 mm per year (Zhao et al., 2025), indicating a rapidly moving thrust setting, as evidenced by six significant earthquakes since 1800 (Felix et al., 2022). This tectonic context underlies Lombok's high earthquake hazard.

Lombok has experienced several significant earthquakes in the past 50 years, most notably the 1979 and 2018 earthquake sequences (Supendi et al., 2020). The epicentre cluster of the 1979 sequence was located in the Lombok Strait, distinctively west of the 2018 sequence, which concentrated in the northern and eastern portions of the island (Supendi et al., 2020). The 2018 earthquake sequence was the deadliest in the island's recorded history, largely attributed to the shallow rupture of the Flores Back-Arc Thrust (Felix et al., 2022). This devastating sequence commenced with a foreshock of magnitude 6.4 on July 29, 2018, followed by the mainshock of magnitude 6.9 on August 5, 2018, and a significant aftershock of magnitude 6.9 on August 19, 2018 (Pramono et al., 2020).

Figure 2 shows that the 2018 Lombok earthquake sequence exhibits clear temporal clustering of seismic events, with distinct peaks in frequency. This study focuses specifically on the major earthquakes within this sequence: the M 6.4 event on July 29, the M 6.9 mainshock on August 5, and the M 6.9 aftershock on August 19. These dates correspond to the highest concentrations of seismic activity, representing the most significant energy releases during the sequence. By concentrating on these three principal events, the analysis captures the primary phases of rupture and the associated large-scale ground deformation, which are critical for understanding the fault geometry and slip behavior of the Flores Back-Arc Thrust system.

InSAR and Coseismic Surface Displacement

InSAR enables dense, extensive spatial measurements, particularly for detecting deformation zones (Raspini et al., 2018; Li et al., 2019). This capability addresses existing gaps and provides a complementary approach to traditional surface-deformation methodologies (He et al., 2020; Del Soldato et al., 2021). Additionally, because InSAR measures deformation along the satellite's line of sight, converting LOS values into vertical displacement is essential for quantifying surface uplift and subsidence (Hayati et al., 2023; Galih & Atriyon, 2025).

Space-based geodetic observations, particularly Interferometric Synthetic Aperture Radar (InSAR), have proven indispensable for characterizing the complex rupture geometry of the 2018 sequence, which occurred on blind faults inaccessible to direct field mapping. Wang et al. (2020) utilized Sentinel-1 InSAR data to invert for slip distributions, revealing that the sequence ruptured a segmented, south-dipping thrust system extending beneath the Rinjani volcanic complex. Their analysis, along with findings by Salman et al. (2020), challenged earlier simple planar fault models by demonstrating that stress transfer between these segments—specifically from the July foreshock to the August mainshocks—played a critical role in the cascading failure of the Flores Back-Arc Thrust.

Despite these advances, the steep topography of the Rinjani volcano and atmospheric noise pose significant challenges for standard InSAR processing, necessitating robust correction methods to accurately resolve near-field deformation. Recent studies have emphasized the importance of separating vertical and horizontal displacement components to distinguish between potential magmatic inflation and tectonic slip (Yang et al., 2020). Furthermore, integrating these geodetic observations with relocated aftershock catalogues has highlighted discrepancies in fault-dip estimates, suggesting that standard Line-of-Sight (LOS) analysis alone may struggle to decouple trade-offs between fault geometry and slip magnitude in such complex back-arc environments (Sasmi et al., 2020). This underscores the necessity for incident-angle corrected analyses to refine the decomposition of deformation vectors and improve hazard assessment models.

Coseismic surface displacement provides critical insight into the distribution of fault slip and bridges observations of rupture at depth with near-surface deformation, thereby improving fault geometry models, slip inversions, and seismic hazard assessments (Song et al., 2024). Surface displacement measurements also corroborate field observations and enhance the interpretation of ruptures (Gold et

al., 2021). Accordingly, this study analyzes the coseismic surface displacement of the 2018 sequence using incident-angle corrected InSAR analysis to improve the understanding of fault behavior.

METHODOLOGY

Data Collection

Table 1. List of Raw Data

No	Sentinel 1 SLC Date	Sets	Incident Angle (i)	Track
1	27 July 2018	1	43.665	Ascending
2	02 August 2018	1,2	43.665	Ascending
3	08 August 2018	2,3	43.665	Ascending
4	20 August 2018	3	43.665	Ascending

Data Processing and Analysis

The Interferometric Synthetic Aperture Radar (InSAR) processing workflow was implemented in the Sentinel-1 Toolbox to derive precise ground deformation measurements from Single Look Complex (SLC) data. As illustrated in Figure 3, the procedure commenced with the coregistration of the master and slave images using the S1 TOPS Coregistration module, which ensures sub-pixel alignment essential for maintaining phase coherence in the Interferometric Wide (IW) swath mode (Yagüe-Martínez et al., 2016). After the initial interferogram was formed, the distinct bursts inherent to the TOPS acquisition mode were merged via a debursting process to create a continuous phase field. To isolate the deformation signal, the topographic phase contribution was simulated and removed using a reference Digital Elevation Model (DEM), after which the residual phase noise was significantly reduced by the Goldstein phase-filtering algorithm (Goldstein & Werner, 1998). The resulting filtered phase was then unwrapped using the Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (SNAPHU) to resolve the 2π ambiguity and reconstruct the continuous deformation field (Chen & Zebker, 2002).

Subsequent to phase unwrapping, the absolute phase values were converted into Line-of-Sight (LOS) displacement maps; however, standard LOS measurements are inherently distorted by the satellite's side-looking geometry. To mitigate these geometric distortions and enhance the accuracy of the deformation data relative to the terrain, a specialized correction was applied in the final stage to generate the Corrected Surface Displacement (CSD). This process involved integrating the local incident-angle maps exported during the processing chain to normalize the LOS displacement, thereby accounting for variation in look angle across the swath (Fialko et al., 2001). This incident-angle correction is particularly critical for analyzing the 2018 Lombok sequence, as the steep gradients of the Rinjani volcanic complex can otherwise introduce significant geometric biases into the estimated fault slip (Wang et al., 2019)

Corrected Surface Displacement

The workflow concludes with a Corrected Surface Displacement (CSD) step, which refines the standard Line-of-Sight (LOS) data. To mitigate geometric distortions caused by the satellite's side-looking geometry, the CSD is calculated by normalizing the LOS displacement with the local incident angle (i) using the equation (1):

$$CSD \text{ (Corrected Surface Displacement)} = \frac{LOS \text{ Displacement}}{\cos(i)} \quad (1)$$

This correction accounts for variation in the look angle across the swath, providing a more accurate representation of surface deformation, particularly in areas with steep topography, such as the Rinjani volcanic complex.

RESULT AND ANALYSIS

LOS Displacement vs Corrected Surface Displacement

Table 2. Details of LOS and CSD

Location	LOS Displacement (cm)			Corrected Surface Displacement (cm)		
	29-Jul	05-Aug	19-Aug	29-Jul	05-Aug	19-Aug
Anyar	9.53	24.02	2.56	13.16	33.19	3.54
Batu Keruk	2.88	30.67	1.62	3.98	42.38	2.07
Baturakit	1.33	28.38	2.27	1.83	39.22	3.14
Bayan	4.99	24.21	3.70	6.89	33.46	5.11
Belanting	-1.68	12.90	22.36	-2.53	17.83	31.21
Bilok Pitung	-0.43	16.28	6.81	-0.68	22.49	9.32
Darakunci	-0.82	9.60	29.18	-1.02	13.26	40.57
Genggelang	-0.78	26.75	5.63	-0.84	36.96	7.08
Gili Air	3.31	35.15	1.22	4.91	48.58	2.09
Gili Meno	1.39	28.14	1.10	1.54	38.89	2.56
Gili Trawangan	1.83	23.00	4.16	2.66	31.78	5.98
Gondang	5.70	31.02	2.53	7.83	42.87	2.95
Gumantar	-3.72	32.83	0.46	-2.75	45.37	0.10
Gunjanasri	-0.98	34.64	0.50	-1.35	47.87	0.69
Kayangan	1.55	42.67	-0.48	2.12	58.97	-0.79
Loloan	7.92	22.87	3.79	10.81	31.61	5.39
Malaka	1.26	20.31	4.18	2.66	28.07	6.87
Mataram	3.30	-2.53	1.41	4.44	-3.50	1.88
Montongpal	7.45	42.67	0.71	10.30	58.96	0.98
Mt. Rinjani	-9.70	15.57	-1.54	-13.45	21.52	-1.78
Mumbulsari	1.05	33.92	1.51	1.40	46.87	2.21
Obelobel	4.50	15.55	13.02	3.71	21.49	17.89
Pansor	-0.80	27.62	0.84	-1.11	38.17	1.16
Pemenang	3.35	32.82	3.27	4.73	45.36	4.33
Pendua	0.53	30.38	0.37	0.35	41.99	-0.10
Rempek	1.73	35.40	0.23	2.40	48.92	0.32
Sajang	-7.39	12.70	7.81	-10.29	17.55	10.86

Location	LOS Displacement (cm)			Corrected Surface Displacement (cm)		
	29-Jul	05-Aug	19-Aug	29-Jul	05-Aug	19-Aug
Salut	-0.45	36.77	1.38	-0.62	50.81	1.91
Sambelia	1.01	10.52	15.75	1.40	14.54	21.76
Sambikelen	7.63	18.38	5.39	10.53	25.40	7.52
Santong	0.15	27.22	0.08	0.20	37.61	0.11
Selengen	0.44	44.94	-0.30	0.61	62.10	-0.41
Semabalunbungung	-7.47	14.83	2.94	-10.33	20.49	4.06
Semabalunlawang	-7.49	14.94	5.98	-10.35	20.65	8.27
Senaru	0.08	19.67	2.45	-0.08	27.19	3.76
Senggigi	5.50	1.48	2.22	7.60	2.05	3.05
Sugian	0.58	10.86	27.74	0.81	15.00	38.33
Sukadana	7.16	26.16	1.37	9.89	36.14	1.90
Tanjung	0.94	40.64	2.21	1.25	56.16	2.95
Teniga	5.09	26.55	4.09	7.04	36.70	5.65

The Line-of-Sight (LOS) and Corrected Surface Displacement (CSD) data reveal a complex spatiotemporal pattern of deformation driven by the segmented rupture of the Flores Back-Arc Thrust (Felix et al., 2022). The data presented in the table underscore the critical importance of incident-angle corrections for accurately resolving the true magnitude of ground deformation, particularly in the rugged topography of northern Lombok, where standard geodetic models often encounter non-uniqueness issues (Zhao et al., 2024).

Magnification of Deformation via Incident-Angle Correction

A comparison of the raw LOS displacement and the CSD values shows that standard LOS measurements significantly underestimate the magnitude of true surface deformation. For instance, during the August 5 mainshock, the recorded LOS displacement at **Kayangan** was 42.67 cm, whereas the CSD reached 58.97 cm. This discrepancy arises because the LOS measures only the one-dimensional scalar projection of deformation along the satellite's look vector (Wibowo et al., 2021). By applying the correction factor, the analysis retrieves a more accurate estimate of the vertical and dip-parallel slip components. This correction is particularly vital for this sequence, as the steep south-dipping geometry of the blind thrust fault creates a deformation field that is not perfectly aligned with the satellite's incidence angle (Yang et al., 2020). The amplified CSD values confirm that the August 5 event involved substantial vertical uplift

exceeding 50 cm in the northern coastal sectors (e.g., **Gondang** at 42.87 cm and **Montongpal** at 58.96 cm), consistent with the rupture of a shallow ramp on the Flores Thrust (Gunawan et al., 2023).

Spatiotemporal Migration of Rupture Zones

The displacement data tracks the eastward migration of the rupture sequence, corroborating a cascading failure of adjacent fault segments:

July 29 (Foreshock): Deformation was localized but geologically distinct. The **Sembalun** region (Sembalunbambung and Sembalunlawang) recorded significant negative CSD values (~ -10.3 cm), indicating subsidence. This localized subsidence is consistent with recent findings that the July 29 event induced distinct deflation or flank instability around the Rinjani volcanic complex, contrasting with the uplift observed in coastal areas such as **Anyar** (13.16 cm) (Afif et al., 2021).

August 5 (Mainshock): This event dominated the sequence, producing widespread uplift across the entire northern coast. Locations like **Selengen** and **Kayangan** reached their peak displacements (62.10 cm and 58.97 cm, respectively). The data show that the rupture propagated bilaterally but concentrated slip on the central-northern segment of the back-arc thrust, driving the massive uplift that caused extensive damage in North Lombok (Felix et al., 2022).

August 19 (Aftershock): The locus of deformation shifted decisively eastward. While western stations like **Gili Air** saw minimal movement (2.09 cm) compared to August 5, eastern stations like **Belanting** and **Obelobel** recorded their highest CSD values of the entire sequence (31.21 cm and 17.89 cm, respectively). This eastward shift confirms the activation of a separate fault segment east of the Rinjani complex, triggered by stress transfer from the earlier mainshocks (Gunawan et al., 2023).

DISCUSSION

Volcanic-Tectonic Interplay

The data notably highlight the interaction between tectonic slip and volcanic structures. The persistent subsidence or lower uplift values around Mt. Rinjani (CSD of -13.45 cm on July 29) compared to the coastal uplift suggest a complex decoupling in which the volcanic edifice responds differently to tectonic stress than the sedimentary accretionary prism to the north (Zhao et al., 2024). The CSD method effectively unmask these subtle variations, proving that the deformation was not a uniform block uplift but a heterogeneous response influenced by the island's volcanic loading and fault segmentation (Yang et al., 2020).

Mt. Rinjani and Sembalun Subsidence during Foreshock: Key to the Mainshock

Figure 7 illustrates the ground displacement following the foreshock of the Lombok earthquake sequence on July 29, 2018. The map specifically highlights the spatial distribution of subsidence

(downward movement) centered around the Mt. Rinjani volcanic complex and the Sembalun plateau. As shown by the displacement scale, the land surface dropped by approximately 0.1 meters in the most affected regions (dark blue). This localized deformation is critical because it suggests that the initial seismic energy was not merely a tectonic release but was deeply influenced by the mechanical properties of the volcanic edifice and the surrounding Sembalun sedimentary basin (Yang et al., 2020). The proximity of the red star, representing the epicenter, to the northern coast indicates that the rupture originated near the Flores Back-Arc Thrust, subsequently triggering the internal settlement of the volcanic flanks observed in the figure (Supendi et al., 2020).

Critically, the subsidence pattern depicted in Fig. 7 provides evidence for the "leaky" nature of the crust around active volcanic arcs. Unlike purely tectonic earthquakes, where displacement is often lateral or uplift-dominant at the fault, the concentration of subsidence in the central mountain region suggests magmatic-tectonic interaction (Yang et al., 2020). The 0.1-meter drop may indicate the compaction of loose volcanic tephra or the depressurization of hydrothermal systems (Hamling et al., 2015) triggered by the foreshock's dynamic stress. Stress resulting from this process poses a greater risk of inducing a major seismic event compared to the seismicity associated with unloading (Yu et al., 2022). Thus, this will further compress the Flores Back-Arc Thrust. Furthermore, the sharp gradient between the stable coastal areas and the inland subsidence zone implies that the Sembalun fault system acted as a structural boundary, focusing the deformation within the caldera region rather than allowing it to dissipate evenly across the island (Yang et al., 2020).

The significance of this subsidence, labeled as the "Key to the Mainshock," lies in its role as a precursor to the larger seismic events that followed in August 2018. Seismologists argue that this initial ground deformation altered the Coulomb failure stress on adjacent fault segments, thereby priming the Flores Thrust for a larger rupture (Yang et al., 2020). The subsidence in Mt. Rinjani likely reflects a loss of structural integrity in the shallow crust, which redistributed tectonic load toward the deeper, more locked sections of the fault (Salman et al., 2020). By mapping this displacement, researchers can better understand the cascading nature of earthquake sequences in volcanic regions, where a foreshock may create a subsidence-driven stress imbalance that necessitates a larger readjustment (the mainshock) (Castro, 2023; Petersen, 2021). This specific spatial data is vital for assessing future slope stability on Mt. Rinjani, which remains a high-risk area for secondary hazards like landslides (Guerreiro et al., 2021).

Conclusion

This study reconstructed the surface deformation field of the 2018 Lombok earthquake sequence, demonstrating the critical importance of correcting for satellite viewing geometry. The following key conclusions are derived from the analysis:

- **Magnification of Deformation:** Standard Line-of-Sight (LOS) analysis alone is insufficient for decoupling fault geometry in the steep terrain of northern Lombok. Application of incident-angle

corrections yielded significantly higher vertical uplift values, exceeding 50 cm in areas such as Gondang and Montongpal

- **Spatiotemporal Migration:** The sequence exhibited a clear cascading failure of adjacent fault segments. The rupture propagated from a localized deformation zone in the west (July 29) to a massive central-northern uplift during the August 5 mainshock and finally to the eastern sectors during the August 19 aftershock.
- **New insight into earthquake foreshock:** A pivotal finding is the detection of localized subsidence (~ 10 cm) centered on the Mt. Rinjani volcanic complex during the July 29 foreshock. This deformation indicates that the initial event involved a complex interaction between tectonic slip and volcanic flank instability. The subsidence likely redistributed tectonic load to locked fault sections, thereby triggering the larger mainshock sequence in August.
- **Volcanic-Tectonic Decoupling:** The Corrected Surface Displacement (CSD) effectively unmasked the heterogeneous response of the island, proving that the deformation was not a uniform block uplift but rather a complex interplay where the volcanic edifice responded differently to stress than the sedimentary accretionary prism

[LIMITATION]

The application of this CSD analysis is subject to specific constraints. The model is restricted to the thrust fault mechanism, thereby excluding potential noise or variability arising from fault rake complexities. Additionally, the calculation is limited to the three major events of the sequence; as a result, minor displacements occurring within this timeframe due to smaller aftershocks are not included in the cumulative assessment.

Declarations

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The authors received no specific funding for this work

[CONSENT TO PUBLISH]

Not applicable as this research is a single-person work.

[ETHICS AND CONSENT TO PARTICIPATE]

Not applicable.

[AUTHOR CONTRIBUTION]

This paper is made by single author. Author contributed to the study conception and design. Material preparation, data collection and analysis were performed by Guruh Sukarno Putra. The draft of the manuscript was written by Guruh Sukarno Putra.

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Figures

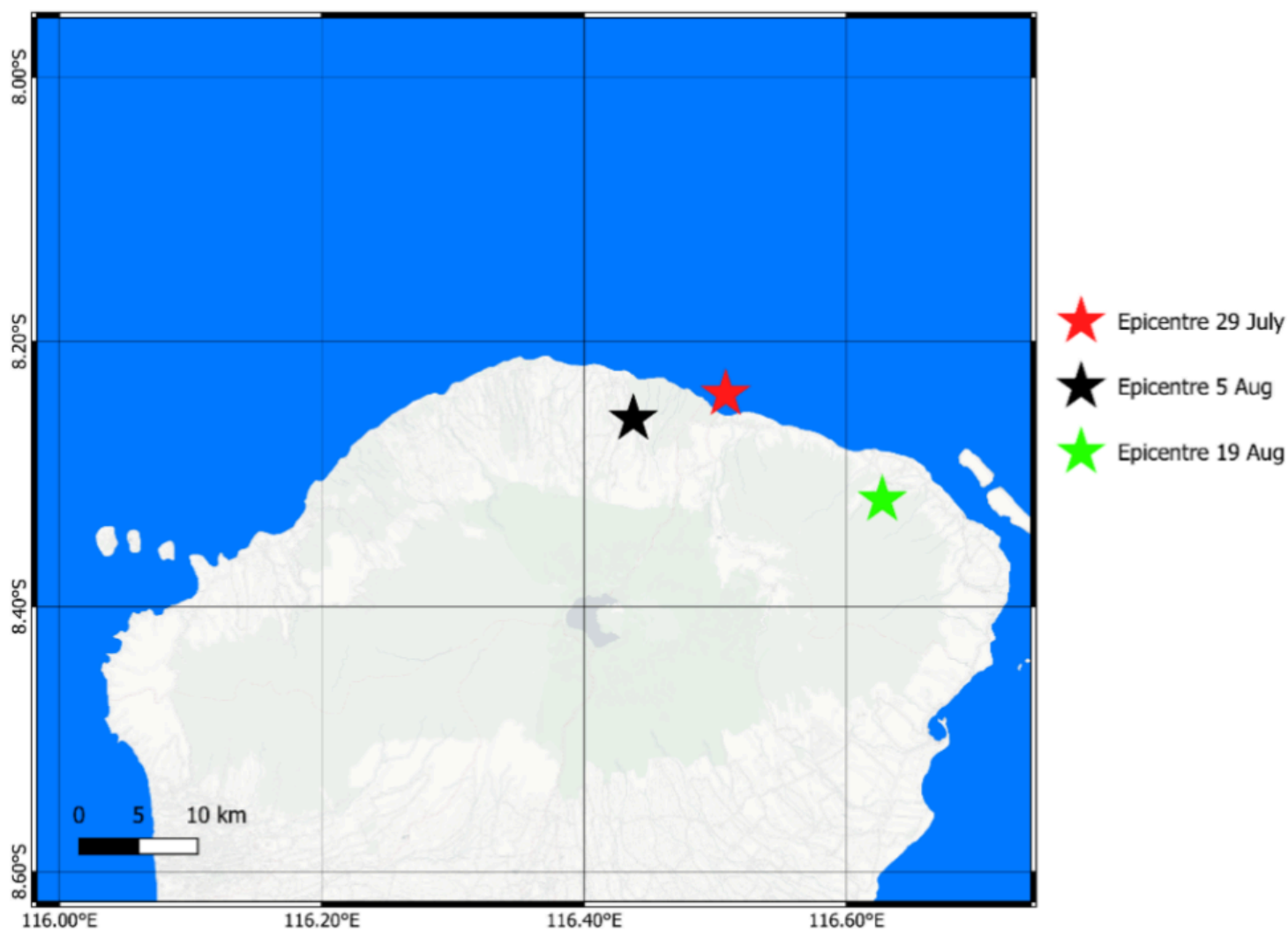


Figure 1

Three-event cluster in this study

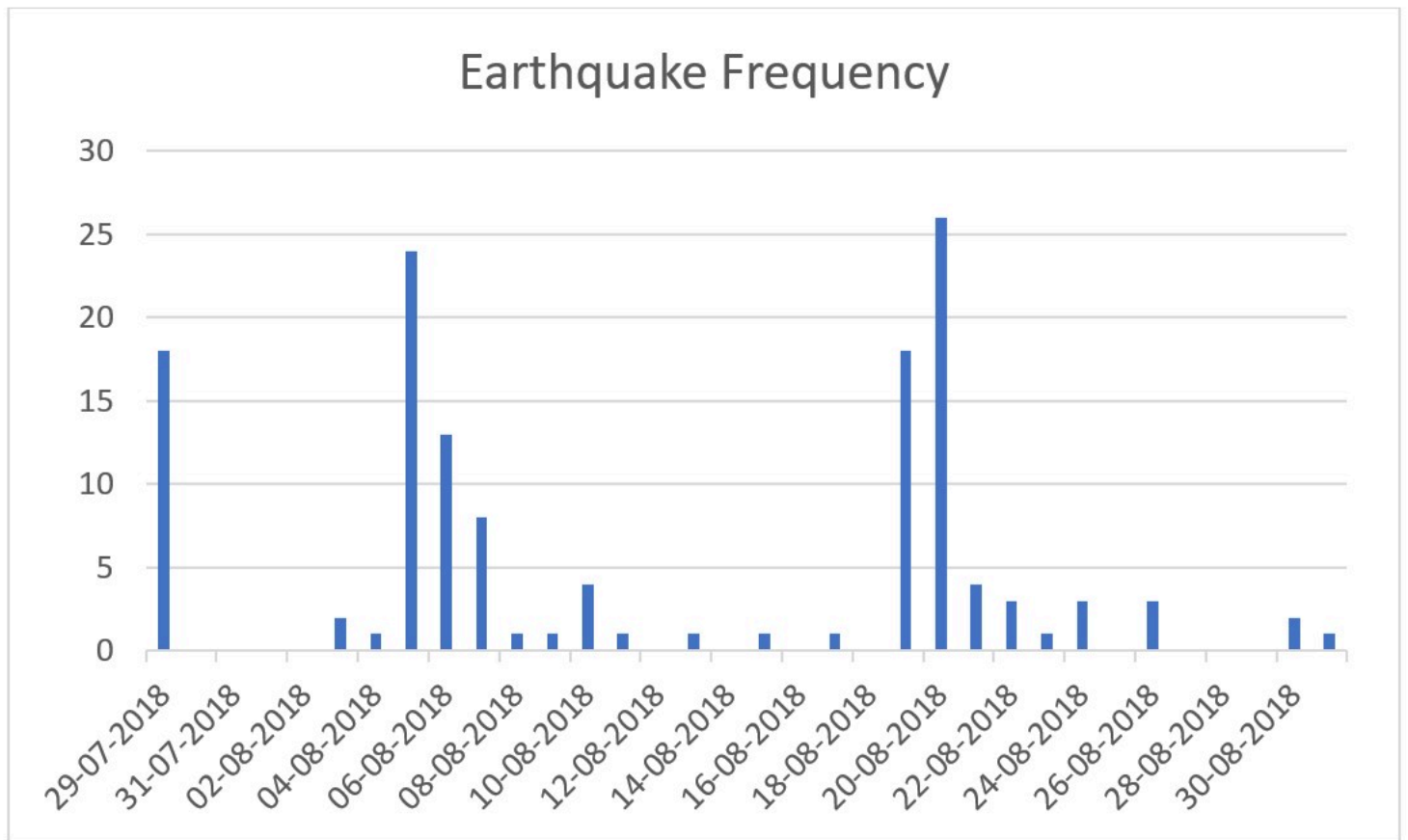


Figure 2

Earthquake Frequency Distribution of the 2018 Lombok Earthquake Sequence

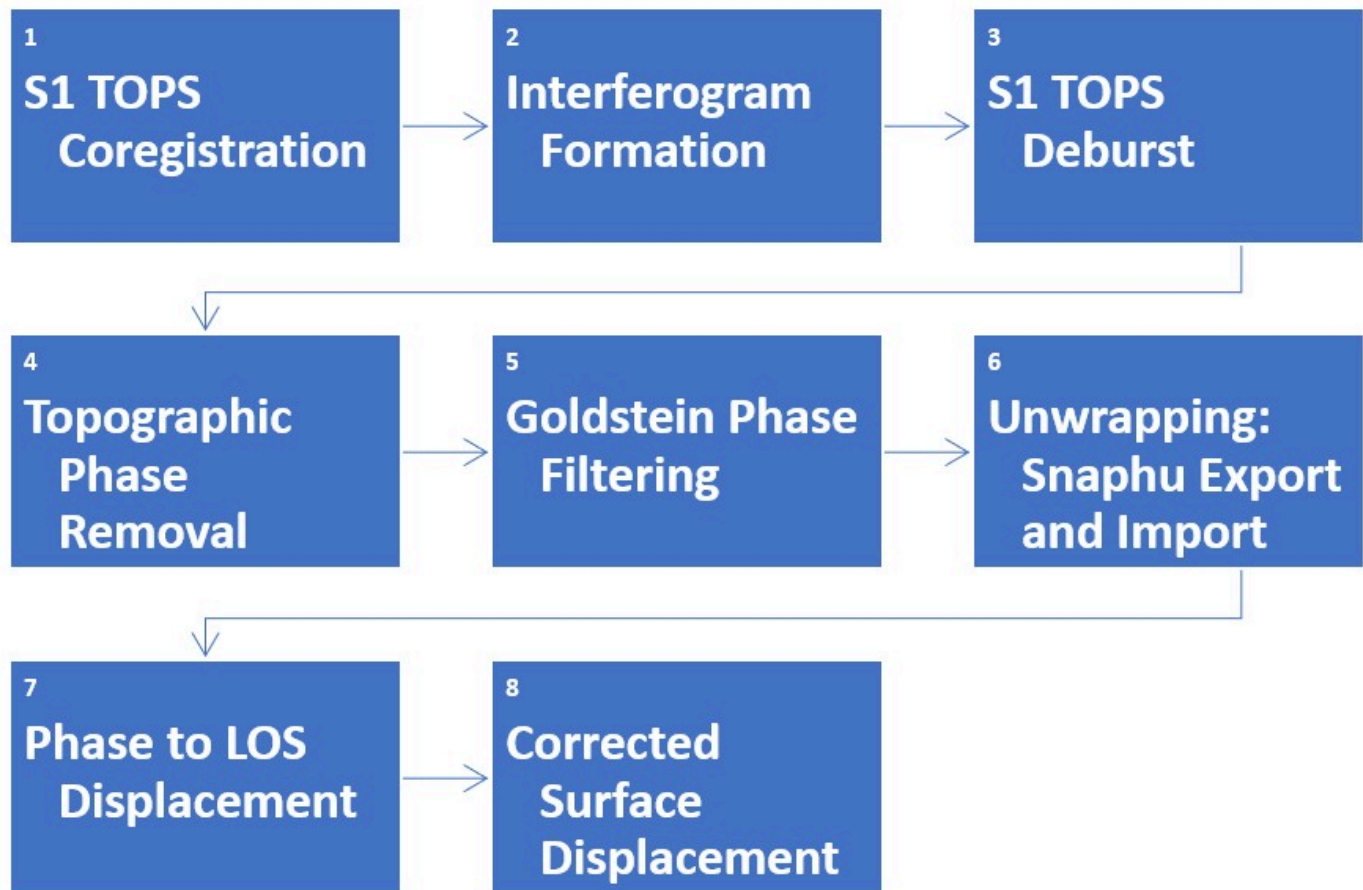


Figure 3

Data Processing Steps

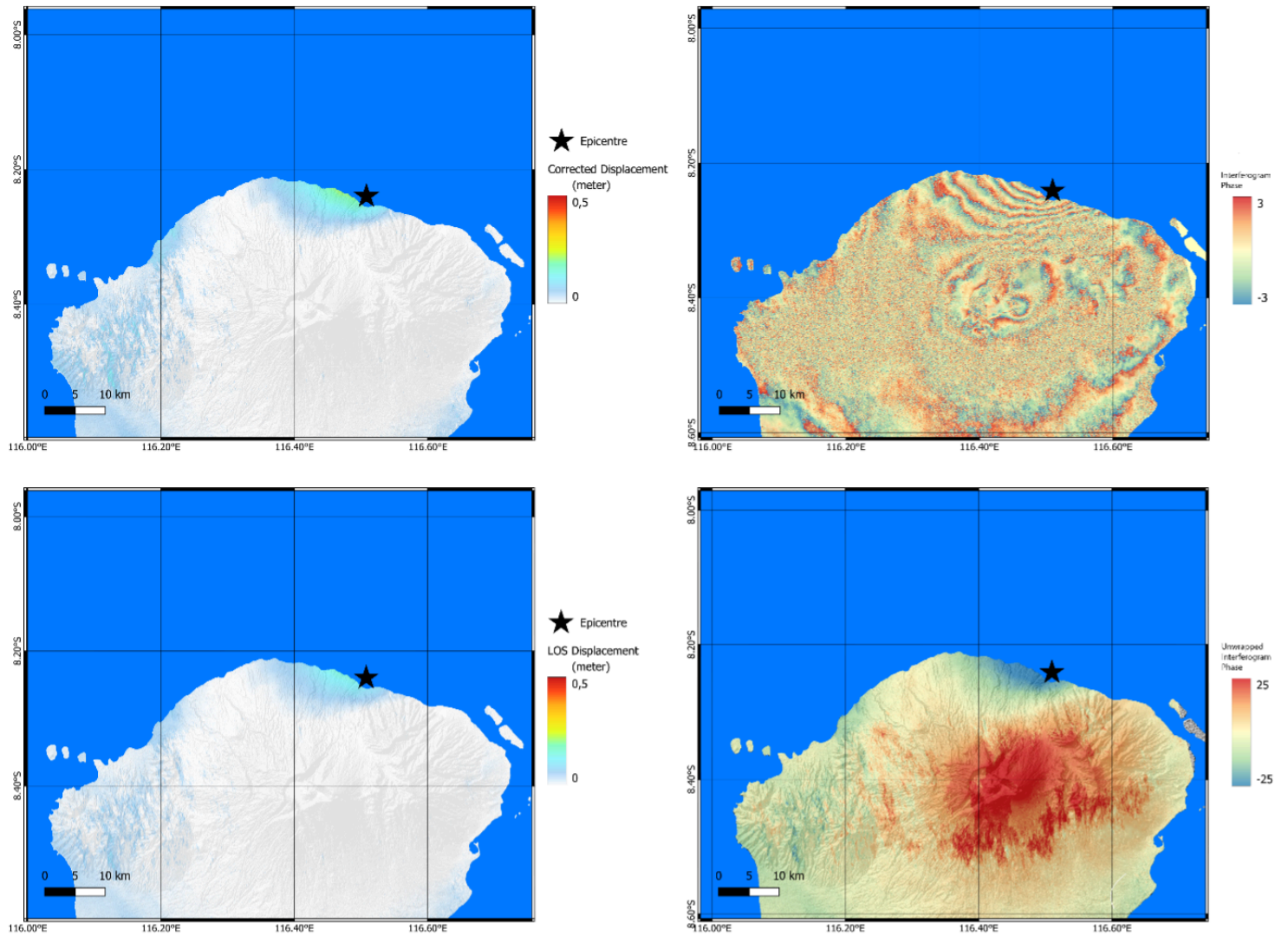


Figure 4

Visualization of the 29 July 2018 Earthquake (Wrapped and Unwrapped Interferogram Phase, LOS Displacement, and Corrected Displacement)

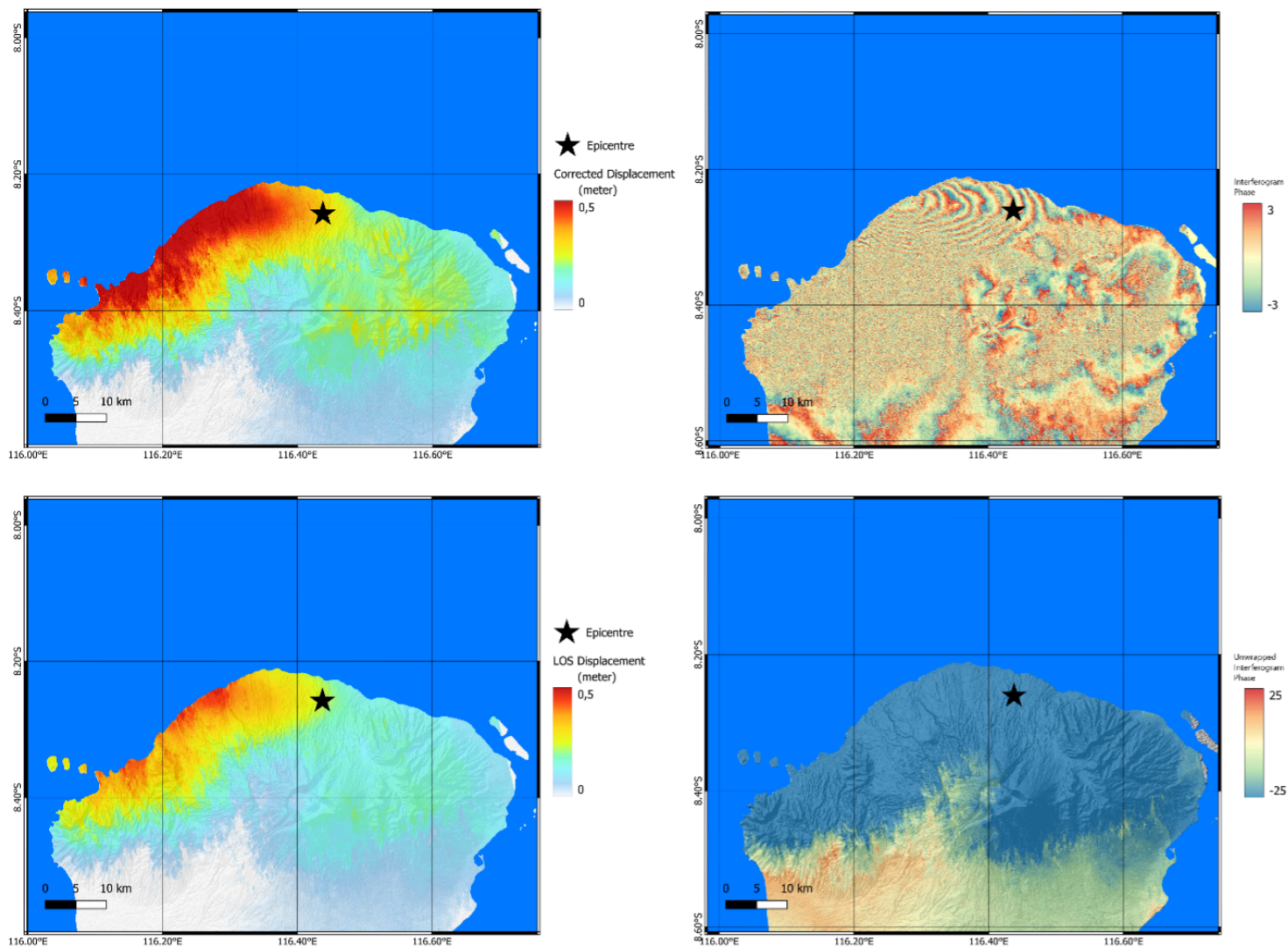


Figure 5

Visualization of the 5 August 2018 Earthquake (Wrapped and Unwrapped Interferogram Phase, LOS Displacement, and Corrected Displacement)

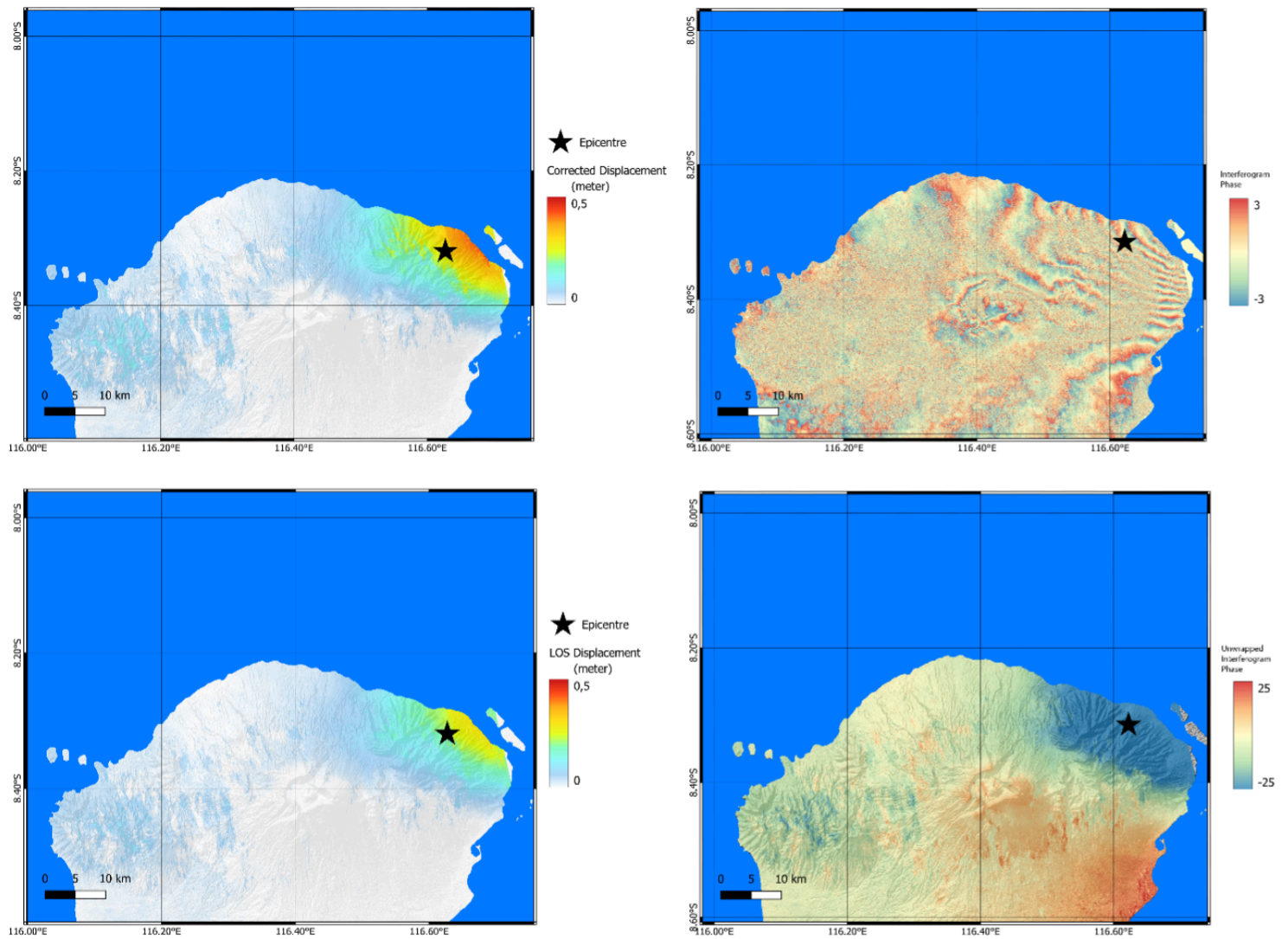


Figure 6

Visualization of the 19 August 2018 Earthquake (Wrapped and Unwrapped Interferogram Phase, LOS Displacement, and Corrected Displacement)

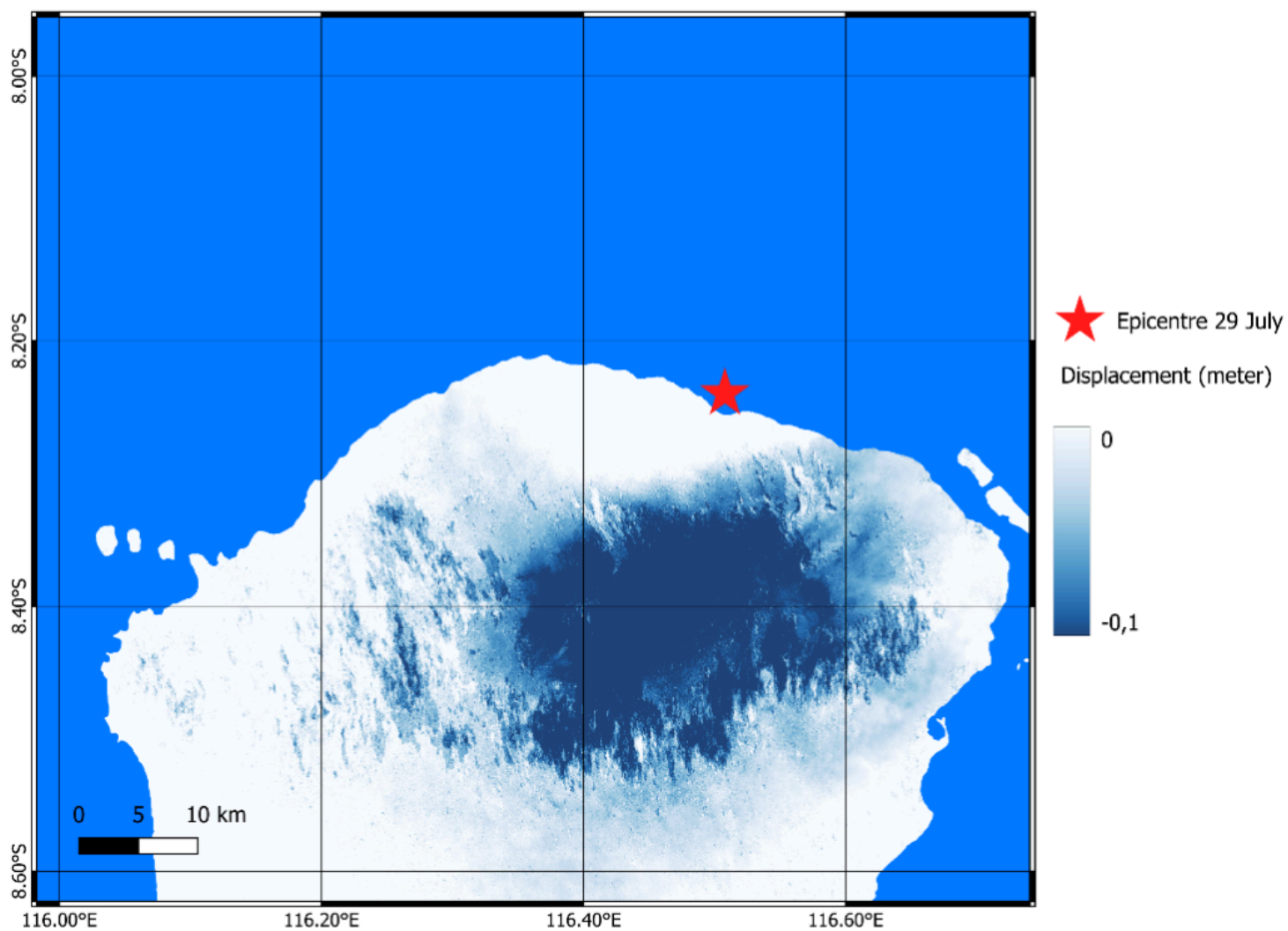


Figure 7

Mt. Rinjani and Sembalun Crater Rim Subsidence during 29 July 2018