REPORT
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A multiple asymmetric bilateral rupture sequence derived from the peculiar teleseismic P-waves of the 2025 Mandalay, Myanmar earthquake

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Abstract A large strike-slip earthquake occurred in central Myanmar on March 28, 2025. The aftershock distribution suggests that the rupture of the mainshock propagated mainly to the south. However, a large-amplitude phase lasting 20 s, followed by a short-period pulse-like phase, were observed at the stations on the north side of the source, while on the south side, multiple peaks without dominant phases continued for 90 s. Using the potency density tensor inversion method, we explain the ”unusual” waveform signature of the Myanmar earthquake by a multiple, asymmetric bilateral rupture, involving boomerang-like back-rupture propagation and supershear.

บทคัดย่อ แผ่นดินไหวขนาดใหญ่ที่เกิดจากรอยเลื่อนแนวระนาบในประเทศพม่า ณ วันที่ 28 มีนาคม พ.ศ. 2568 แสดงการกระจายตัวของอาฟเตอร์ช็อกและชี้ให้เห็นทิศทางกระบวนการเกิดรอยแตกของแผ่นดินไปทางทิศใต้จากจุดกำเนิดแผ่นดินไหว อย่างไรก็ตามความผิดปกติของคลื่นไหวสะเทือนที่บันทึกจากสถานีวัดทางตอนเหนือของแหล่งกำเนิดแสดงคลื่นแอมปริจูดสูงในช่วงระยะเวลา 20 วินาทีแรกตามด้วยพัลส์คลื่นคาบสั้น ในขณะที่คลื่นที่วัดได้จากสถานีทางใต้ของจุดกำเนิดแสดงคลื่นแอมปริจูดสูงต่อเนื่องโดยไม่มีพัลส์เด่นจนถึงวินาทีที่ 90 จากผลการวิเคราะห์กลไกการการเกิดรอยแตกของแผ่นดิน ณ ขณะเกิดแผ่นดินไหวด้วยวิธีการผกผันค่าความหนาแน่นเทนเซอร์สามารถอธิบายความผิดปกติของสัญญาณคลื่นแผ่นดินไหวโดยแผ่นดินไหวในพม่าครั้งนี้เกี่ยวข้องกับการแยกตัวแบบไม่สมมาตรไปทางทิศเหนือและทิศใต้ อีกทั้งยังเกี่ยวข้องกับทิศทางการแตกตัวแผ่นดินแบบย้อนกลับและการแตกตัวเหนือความเร็วเฉือนหรือที่เรียกว่าแผ่นดินไหวซุปเปอร์เชียร์

要旨 2025 年 3 月 28 日ミャンマー中部で大地震が発生した。観測された遠地実体波 P 波は、震源北部に位置する観測点において大振幅かつ鋭いパルス状のシグナルが観測される一方で、震源南部に位置する観測点においては孤立するパルス状のシグナルは見えず、微動を想起させるスパイク状の複数のシグナルが 90 秒ほど続くなど、余震分布から予想される震源南方への破壊指向性とは相容れない特異な特徴をもつ。本研究は高自由度な震源過程解析手法であるポテンシー密度テンソルインバージョンを 2025 年ミャンマー地震の遠地実体波 P 波に適用し、ブーメランのような逆破壊伝播や超せん断破壊を含む複数の非対称なバイラテラルな破壊を組み合わせたモデルで、特異な遠地実体波 P 波の特徴を説明できることを明らかにした。

Non-technical summary On March 28, 2025, a large and devastating earthquake occurred in central Myanmar. We used globally observed seismic records to build the source process model of the large earthquake and reveal how the earthquake rupture evolved along the fault. We find that the earthquake ruptured a fault segment of 400 km length, in 80 s. Within the broad apparent southward fast rupture, the detailed rupture evolution was complex, being characterized by a series of discrete sub-events, involving bi-directional, southward and northward ruptures that migrated at fast speeds, partly faster than the seismic shear waves can travel. These findings are critical for our understanding of earthquake-rupture dynamics and assessing the associated earthquake hazard.

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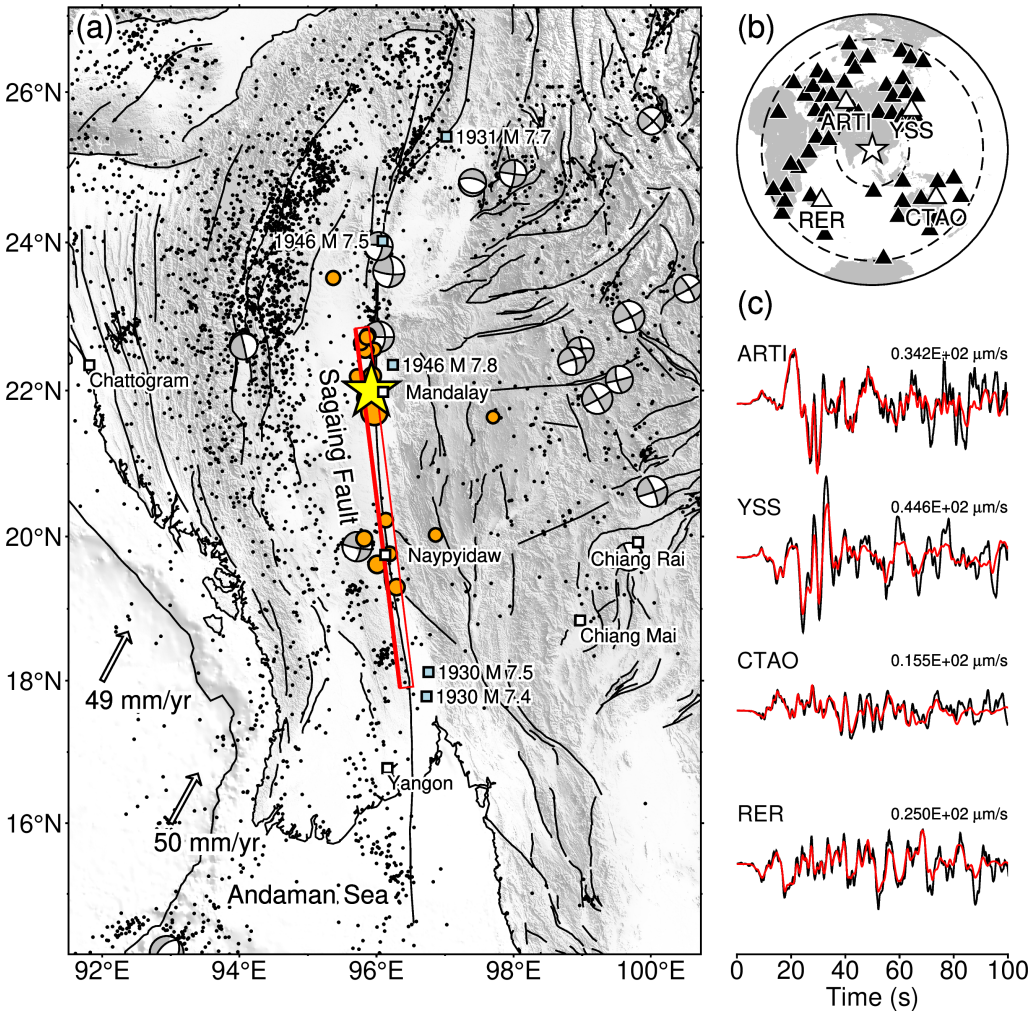


Figure 1 (a) Summary of the study region. The star and the orange circles show the mainshock epicenter and the three-day aftershocks (U.S. Geological Survey Earthquake Hazards Program, 2017; USGS, 2025), respectively. The black dots are available earthquakes in this region from the USGS catalog (M>3, before March 27, 2025) (U.S. Geological Survey Earthquake Hazards Program, 2017). The blue square markers show previous large (M>7) events on the Sagaing fault (Hurukawa and Maung Maung, 2011). The beachballs are the available GCMT solutions before the 2025 Myanmar earthquake (Dziewonski et al., 1981; Ekström et al., 2012). The rectangle outlines the model plane used for our inversion with the thicker line representing the model top. The black lines are the active faults (Styron and Pagani, 2020). The arrows show relative plate motions (DeMets et al., 2010). The background topography is from SRTM15+V2 (Tozer et al., 2019). (b) The station distribution (triangles) used for our inversion. The white triangles show the stations corresponding to the traces in Fig. 1c. The dashed circles show epicentral distances of 30° and 90°. The star shows the epicenter. (c) Selected traces of the observed (black) and synthetic (red) waveforms. The trace sampling interval is 0.05 s, and an anti-aliasing filter is applied. The corresponding stations are shown as white triangles in Fig. 1b. The maximum amplitude of the observed trace is on the right of each panel. All the traces used in our inversion are displayed in Fig. S1.

1 Introduction

On March 28, 2025, a moment magnitude (M_W) 7.7 earthquake occurred around 20 km west of Mandalay in Myanmar (Fig. 1a). According to the U. S. Geological Survey (USGS) (USGS, 2025), the epicenter is located at 21.996°N, 95.926°E and the aftershocks are distributed in an area spanning from 21.7°N to 23°N latitude (Fig. 1a), suggesting that the main rupture propagated to the south from the epicenter. In and around the possible source region, the right-lateral Sagaing fault extends for about 1200-km, from northern Myanmar to the Andaman Sea (Fitch, 1972; McCaffrey, 1992; Bertrand and Rangin, 2003; Socquet et al., 2006; Wang et al., 2014; Sloan et al., 2017; Xiong et al., 2017; Lindsey et al., 2023) (Fig. 1a). Around the Sagaing fault, the India plate is moving against the Eurasia plate at a rate of about 50 mm/yr (DeMets et al., 2010) (Fig. 1a). The possible rupture area is located in the central part of the Sagaing fault, which has been considered as a seismic gap, being prone to host a large earthquake (Fadil et al., 2023; Hurukawa and Maung Maung, 2011; Tha Zin Htet Tin et al., 2022; Yang et al., 2024). The earthquake has severely affected Myanmar and surrounding areas, causing significant damage to the infrastructure and people (e.g., Witze, 2025).

At the observation stations on the north side, large-amplitude waves were observed for 20 s after the P-wave first arrival and short-period pulse-like waves were observed following the large-amplitude phase (Fig. 1c).

At the observation stations on the south side, multiple peaks without dominant phases (hereafter we call these phases as "tremor-like phases") continued until about 90 s after the P-wave first arrival. The aftershock distribution may suggest that the propagation of the mainshock rupture was southward (Fig. 1a). However, it is notable that the high-amplitude pulse-like waveform is not clearly observed at the stations in the expected rupture direction but rather identified at the stations on the north side of the epicenter (Fig. 1c). This simple yet peculiar observation hints at the difficulty in explaining the "unusual" teleseismic P-waves of the Myanmar earthquake only via a simplified seismic source model, and suggests the necessity of flexibly analyzing, with a high-degree-of-freedom, the seismic source process by allowing changes in the focal mechanism and rupture speed and direction, including possible back-rupture propagation and supershear (e.g., Hicks et al., 2020; Okuwaki et al., 2020) along the mainshock fault.

In recent years, based on the approach of Yagi and Fukahata (2011) who considers the uncertainty of the Green's function originates from a discrepancy between the true and theoretical Green's functions due to inaccuracy of the underground structure, the Potency Density Tensor Inversion (PDTI) method has been proposed (Shimizu et al., 2020; Yamashita et al., 2022b). Using the PDTI, we can estimate the detailed source model, including information on the fault geometry (Shimizu et al., 2020). The PDTI has been applied to many earthquakes in various tectonic settings and has proven effective in estimating complex source processes (e.g., Hicks et al., 2020; Yamashita et al., 2021; Yagi et al., 2023). In this article, we apply the PDTI to the teleseismic P-waves of the 2025 Myanmar earthquake and infer an irregular rupture process involving back-rupture and supershear-rupture propagation, which can explain the peculiarity of the observed waveforms.

2 Method, Data and Model setting

According to the PDTI method (Shimizu et al., 2020; Yamashita et al., 2022b), fault slip occurring on multiple faults is represented by the potency density tensors on an assumed model plane (Shimizu et al., 2020), and the potency density tensors are expressed as the sum of five basis double couples according to Kikuchi and Kanamori (1991), which enables high-degree-of-freedom modeling of source processes, where the potency tensor is calculated by dividing the moment tensor by the rigidity of the medium (Shimizu et al., 2020). Following the approach of Yagi and Fukahata (2011), PDTI incorporates the uncertainty of the Green's function into the data covariance matrix and evaluates the optimal value of the hyperparameters using Akaike's Bayesian Information Criterion (ABIC; e.g., Akaike, 1980; Sato et al., 2022), thereby achieving stable estimation even for a high-degree-of-freedom seismic source model without overfitting. PDTI is formulated using the properties of teleseismic P-waveforms, which have low spatial resolution but are sensitive to changes in focal mechanism solution (Shimizu et al., 2020). In this study, we used the latest version of the PDTI method that introduced the time-adaptive smoothing (Yamashita et al., 2022b).

We used the vertical component of the teleseismic P-waveforms downloaded from the SAGE Wilber 3 system (see Data and code availability). We selected 58 stations that have adequate azimuthal coverage of the source region and sufficiently high enough signal-to-noise ratios to pick the P-wave arrival. We adapted the standard PDTI data processing procedure, which has been verified in previous studies (e.g., Yamashita et al., 2022a). After manually picking the arrival time of the P-wave, the observed waveforms were converted into velocity waveforms. The sampling interval is 0.7 s. The theoretical Green's function was calculated at 0.1 s intervals following the method of Kikuchi and Kanamori (1991), with the 1-D structure of the ak135 model (Kennett et al., 1995; Montagner and Kennett, 1996). We also used four different velocity structures from CRUST1.0(Laske et al., 2013) to evaluate the sensitivity (Text S1). The mainshock epicentral coordinates determined by the USGS were used for the initial rupture point, with the hypocentral depth was set to 18 km, based on an initial analysis. An alternative hypocentral depth of 10 km (e.g., USGS, 2025) was also tested; it turns out that the mainshock hypocentral depth does not significantly affect the inversion solution (Figs. S2, S3).

The strike and dip of the model plane were set to 353° and 60°, respectively, based on the GCMT solution. The length and width of the model plane were set to 468 km and 36 km, respectively. The node spacing was set at 12 km in the strike direction and 5 km in the dip direction. The maximum duration of the potency-rate density function, for each space node, was set to 49 s, and its sampling interval was set to 0.7 s. The total duration of the event was set to 90 s. The hypothetical maximum rupture front velocity was set at 6 km/s to be fast enough for allowing the possibility of supershear rupture. All of the five basis double-couple components were rotated so that the best-fitting double-couple of the GCMT solution would become one of the basis double-couple components (e.g., Yagi et al., 2023), which is designed to effectively apply the time-adaptive smoothing constraint (Yamashita et al., 2022b).

3 Results

The resultant spatiotemporal distribution of the potency-rate density tensors shows multiple rupture episodes. We define at least three rupture episodes. The uncertainty and sensitivity of the solution to the different model settings are evaluated (Text S1 and Figs. S2, S3) using the same set of stations as used for the main model, and in the Results and Discussion sections we focus on the rupture features that are robustly resolved. The synthetic waveforms calculated from the estimated source process model reproduce the complex signatures of the observed waveforms, including the characteristic short-period pulse-like phase and the tremor-like phases with multiple peaks (Figs. 1c, S1).

The E1 episode: the initial rupture propagates from

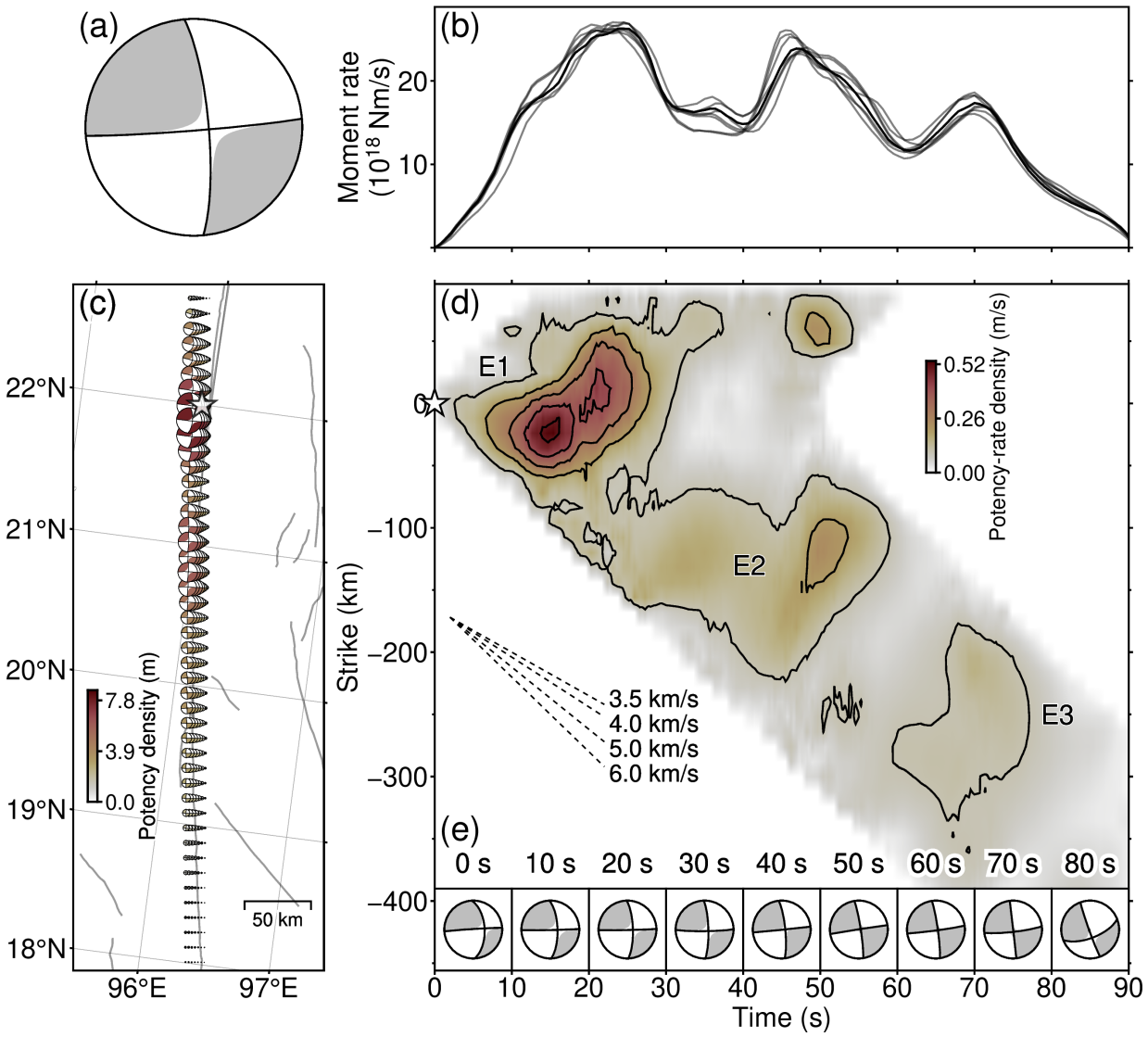


Figure 2 (a) The total moment tensor solution obtained by time-space integral of the potency-rate density tensors in a lower hemisphere projection. (b) The compilation of the moment-rate functions of the alternative models (Text S1). The multiple gray lines and a black line represent the alternative models and the optimum model, respectively. (c) The potency density tensor distribution obtained by time integral of the potency-rate density tensors. The star shows the initial rupture point. The lines show the active faults (Styron and Pagani, 2020). (d) The spatiotemporal evolution of the potency-rate density projected along the strike of the model plane. The contour interval is 0.1 m/s. The star shows the initial rupture point. Black dashed lines represent reference rupture speeds. (e) The snapshots of the moment tensor solution (lower hemisphere projection) of the averaged potency rate in the corresponding 10-s time window. The starting time of each window is shown at the top.

the hypocenter towards the south and shallow region, reaching the ground surface at 6 s from the origin time (OT), and reaching about 40 km south of the epicenter at OT+8 s (Figs. 2d and 3). The main E1 rupture begins at OT+8 s, propagating asymmetrically, in a bilateral way, to the south and north. The southern rupture reaches about 75 km south of the epicenter at OT+16 s, and becomes faint soon after that. The northern rupture propagates near surface, reaching about 65 km north of the epicenter at OT+20 s; the rupture fades from OT+25 s. The northern rupture area tends to be concentrated at shallow depths.

The E2 episode: from OT+24 s, another rupture episode begins around 120 km south of the hypocenter (Fig. 2d). It initially migrates towards both north and south directions, until OT+40 s. From OT+45 s to OT+58 s, the potency-rate density is relatively large throughout the E2 rupture region.

The E3 episode: although the potency-rate becomes relatively faint, and it gets difficult to rigorously infer obvious rupturing paths during OT+60–80 s, the rupture dominates the region of 200–400 km south from the epicenter, where it shows bilateral migration to the south and north (Fig. 2d).

The fault geometry can be inferred from our resultant potency-rate density tensors. We observe the progressive change of the fault geometry from north to south of the model domain (Fig. 2c). The strike direction of the potency-rate density tensors shows counterclockwise rotation from 366° (or 6°) to 352° azimuth, from north to south of the model domain. The dip angle also changes. During E1, the dip is shallow with an angle of 57° for the initial deep-to-shallow-southward rupture, and it gets steeper at 70° for the following domi-

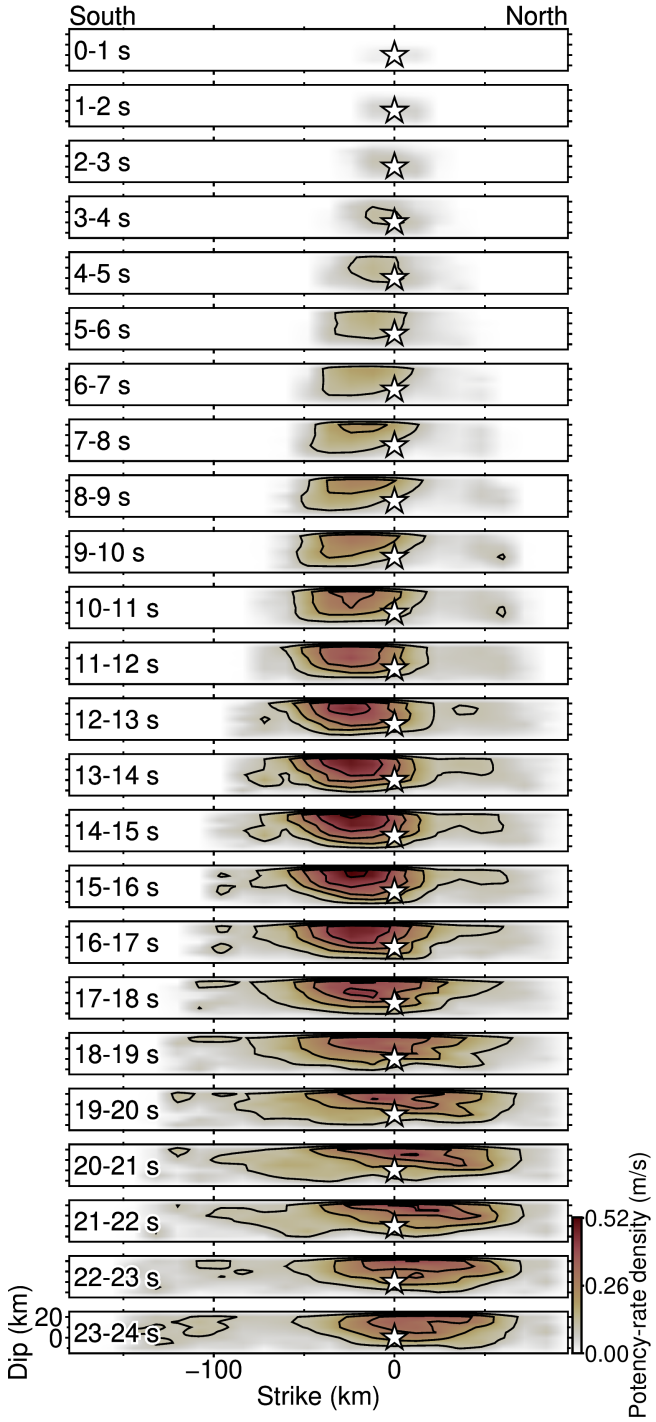


Figure 3 The snapshots of the potency-rate density distribution projected on the model plane. The white star is the initial rupture point. The contour interval is 0.1 m/s. Only the domain around E1 of the model plane is illustrated for visibility reasons. This figure clearly shows the asymmetrical bilateral rupture in E1 around the hypocenter.

nant shallow northward rupture (Fig. 2e). The dip angle becomes steeper in the southern domain, reaching 80° during E2 and 87°–90° during E3 (Fig. 2e).

The potency density tensor distribution obtained by the time-integral of the potency-rate density tensors shows the two dominant peaks, centered at 10 km and 110 km south of the epicenter (Fig. 2c), which correspond to E1 and E2 (Fig. 2d). The total moment tensor solution obtained by time-space integration of the potency-rate density tensors is characterized by strike-slip faulting with a slight inclination of dip (79° for the north-south striking nodal plane) (Fig. 2a), and the seismic moment is 1.3×10^{21} N m (M_{W} 8.0). The moment rate function calculated by spatial integration of the potency-rate density tensors shows three or more peaks (Fig. 2b), which is consistent with the rupture episodes.

4 Discussion and Conclusion

Although the broad rupture process of the 2025 Myanmar earthquake can be characterized by the southward rupture along the Sagaing fault, our study shows that it involves multiple, segmented rupture episodes, including asymmetric bilateral ruptures. We find at least three rupture episodes in our preferred solution. It is difficult to trace the rupture front propagating to the south due to the lower amplitude of the potency-rate density, however, the estimated rupture migration velocity from the start time and location of E2 is about 4.6–5.4 km/s, which is faster than the S-wave velocity around the source region (Table S1). Both E1 and E2 exhibit a bilateral rupture that propagates both in north and south directions. Especially E1 favors the dominant northward rupture that starts at OT+8 s, where the northern wing of the bilateral rupture propagates at about 5 km/s, which is faster than S-wave velocity around the source region (Table S1). As shown in Fig. 1, the seismic records at observation stations on the north side of the epicenter show the large-amplitude phase followed by the sharp, impulsive signal in the earlier part of the traces (Fig. 1c). On the other hand, at observation stations on the south side, the teleseismic P-waves are characterized by tremor-like signatures with multiple peaks. Such a waveform signature can be seen in synthetic tests with variable rupture speed. By comparing the test that uses a normal rupture velocity with another one that produces supershear (Fig. S4), one can notice the relatively higher-amplitude phases at azimuths in the direction of the supershear rupture. The irregular, azimuthal dependence of the waveform signatures may not be explained by a simple unilateral southward rupture; the rupture rather involves a series of bilateral or boomerang-like backward ruptures and supershear ruptures towards north, as found in our PDTI solution.

An advantage of our PDTI method is the simultaneous estimation of fault rupture and geometry. As shown in Fig. 2, the resultant potency density tensors show the gradual, counterclockwise curvature of the strike orientation, which is consistent with the strike orientation of the Sagaing fault (e.g., Styron and Pagani, 2020). The spatial distribution of the dip angles also shows an along-strike variation from north to south of the epicenter: it shows shallow (around 60°–70° dip) dipping in the E1 region, which gets steeper (over 80° dip) in the E2 region. As shown by both the static potency distribution and the potency-rate distribution (Figs. 2c and 2d, respectively), the rupture domains of E1 and E2 are distinctly segmented. Such a segmentation can be robustly seen even if we adopt a different model setting (Figs. S2, S3). The segmentation of the rupture domains together with the spatial variation of the dip angles should char-

acterize the possible along-strike heterogeneity of the Sagaing fault. Note, however, that our segmentation estimates rely on the inversion of teleseismic data, which has less spatial resolution compared to other datasets (e.g., SAR data).

The seismic moment obtained from the PDTI is 2.5 times larger than that of the GCMT solution. With other model settings, the seismic moment ranges from 1.27–1.34 $\times$ 10^{21} N m (M_W 8.0). This discrepancy between the seismic moment estimated by PDTI and a centroid moment tensor inversion may be due to a simplified seismic source model that is insufficient to represent the complex rupture process (Ohara et al., 2023). However, we should note that PDTI is designed to extract the details of the rupture process from the teleseismic P-waves and it does not target the accurate estimation of the seismic moment.

Due to the increase in the quality and quantity of teleseismic data, as well as development of data-driven analysis methods such as the PDTI, it has become possible to stably estimate seismic source processes that can reproduce peculiar observed waveforms like the ones of the 2025 Myanmar earthquake. As a result of applying the PDTI, the current study unearthed the complex seismic source process of the 2025 Myanmar earthquake, involving a series of bilateral or boomerang-like back-rupture propagation and supershear.

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Data and code availability

The source code of the Potency Density Tensor Inversion is available at https://github.com/yujiyagi/pdti_public_version. The models presented in this paper are archived at https://doi.org/10.5281/zenodo.15386684. All seismic data were downloaded through the EarthScope Consortium Wilber 3 system (https://ds.iris.edu/wilber3/) including the following station networks: the G (GEOSCOPE; Institut De Physique Du Globe De Paris (IPGP) and Ecole Et Observatoire Des Sciences De La Terre De Strasbourg (EOST), 1982); the GT (GTSN; Albuquerque Seismological Laboratory (ASL)/USGS, 1993); the IC (NCDSN; Albuquerque Seismological Laboratory (ASL)/USGS, 1992); the II (IRIS/IDA - GSN; Scripps Institution of Oceanography, 1986); the IU (GSN-IRIS/USGS; Albuquerque Seismological Laboratory/USGS, 1988); and the MN (MedNet; MedNet Project Partner Institutions, 1990). The USGS events catalog is searched using https://earthquake.usgs.gov/earthquakes/search/ (U.S. Geological Survey Earthquake Hazards Program, 2017). The moment tensor solutions of the Global Centroid Moment Tensor (GCMT) catalog are available through https://www.globalcmt.org/CMTsearch.html (Dziewonski et al., 1981; Ekström et al., 2012). The ak135 (Kennett et al., 1995; Montagner and Kennett, 1996) and CRUST1.0 (Laske et al., 2013) are available through websites http://rses.anu.edu.au/seismology/ak135/ak135f.html and https://igppweb.ucsd.edu/~gabi/crust1.html, respectively. The active fault data is available at https://github.com/GEMScienceTools/gem-global-active-faults. Plate motion is calculated using Plate Motion Calculator (http://ofgs.aori.u-tokyo.ac.jp/~okino/platecalc_new.html). All figures were generated with Generic Mapping Tools (v6.5.0; https://docs.generic-mapping-tools.org/latest/index.html Wessels et al., 2019).

Competing interests

The authors have no competing interests.

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