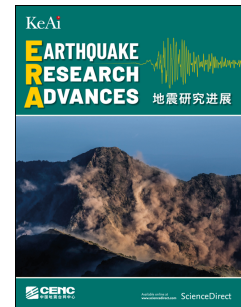


Journal Pre-proof

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PII: S2772-4670(25)00067-3

DOI: <https://doi.org/10.1016/j.eqrea.2025.100424>

Reference: EQREA 100424

To appear in: *Earthquake Research Advances*

Received Date: 24 July 2025

Revised Date: 14 October 2025

Accepted Date: 17 October 2025

Please cite this article as: Gunawan, E., Widiyantoro, S., Hussain, E., Hanifa, N.R., Syafiudin, M.F., Wibowo, S.T., GNSS Constraints on the Jakarta Fault, Indonesia: Resolving Slip Rate and Seismic Hazard Potential, *Earthquake Research Advances*, <https://doi.org/10.1016/j.eqrea.2025.100424>.

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GNSS Constraints on the Jakarta Fault, Indonesia: Resolving Slip Rate and Seismic Hazard Potential

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Abstract

The characteristics of the active faults in the region around the megacity of Jakarta are poorly understood. This study investigates slip rate of the Jakarta Fault using new GNSS data obtained from campaign measurements conducted between 2019 and 2023. This is a recently discovered active fault forming part of the broader Baribis Fault system that runs across most of northern Java. The Jakarta Fault cuts across the southern portion of Jakarta, a city with over 32 million people in the metropolitan region. In this study, we apply a 2-D screw dislocation model to the north-south component of the GNSS velocities, which are projected onto a profile perpendicular to the approximately east-west trending fault. Our analysis estimates a fault slip rate of 3.2 mm/yr, with a locking depth of 7.2 km and a dip angle of 63°. Previous studies have estimated the fault length to be approximately 50 km, with a return period of around 210 years. By combining this information with our findings, we estimate that a potential earthquake of magnitude between 6.49 and 6.54 could occur on the fault. Our research highlights the active deformation occurring along the Jakarta Fault, emphasizing the urgent need for greater attention from stakeholders, as an earthquake of this magnitude could pose significant seismic risks to the Jakarta region.

Keywords: Jakarta Fault, slip rate, locking depth, dip angle, GNSS, seismic hazard

1. Introduction

As the center of economic activity and the most densely populated region in Indonesia, Jakarta is highly vulnerable to natural disasters such as floods and sea-level rise (e.g., Firman et al., 2011). Earthquakes pose another significant hazard, with the potential for devastating impacts on the city. Seismicity typically occurs along active faults and volcanic regions (e.g., Liu and Stein, 2016; Gunawan et al., 2024a), as well as in areas affected by human-induced activities such as groundwater, coal, mineral, gas, oil and hydrocarbon extraction (e.g., Foulger et al., 2018). For Jakarta, this hazard is a direct consequence of the region's active tectonics. The city is situated in the northern backarc region of the Sunda subduction system, a tectonic setting where the India/Australian Plate subducts beneath the Eurasian Plate.

The Sunda Trench located approximately 250–300 kilometers south of Jakarta, marks the primary subduction interface. Between the trench and the city lies a complex geological architecture, comprising the Java megathrust (e.g., Widiyantoro et al., 2020), the forearc basin

(e.g. Susilohadi et al., 2005), the volcanic arc (e.g., Clements et al., 2009), and a system of inland faults such as the Cimandiri Fault (e.g., Marliyani et al., 2016). These features have been shaped by millions of years of plate convergence and deformation.

Based on a previous geological study, Simandjuntak (1993) identified the Baribis–Kendeng Thrust as an active fault in the southern part of Jakarta in EW direction (Figure 1). This investigation utilized geological mapping and geophysical surveys, including seismic reflection profiling, seismicity (earthquake) analysis, gravity, and magnetic studies, conducted collaboratively by the Center for Geological Survey of Indonesia (formerly the Geological Research and Development Center), the British Geological Survey (BGS), the Institute for Petroleum and Natural Gas (Lemigas), the State Oil and Natural Gas Mining Company (Pertamina), and private oil companies. A recent geological study by Aribowo et al. (2022) further delineated the Baribis-Kendeng fault system in northern West Java, introducing the new term "Java Back-arc Thrust" to describe the thrust mechanism observed along this west-to-east trending fault zone.

Historically, Jakarta has experienced damaging earthquakes, such as those on 5 January 1699, 22 January 1780, and 10 October 1834 of $\sim$ Mw 7.4 (Griffin et al., 2019; Koulali et al., 2017; Nguyen et al., 2015). However, the specific fault sources responsible for these events remain poorly understood. For instance, Nguyen et al. (2015) attribute the 1780 and 1834 events to the Jakarta Fault, which is considered a segment of the broader Baribis-Kendeng fault system. These findings suggest that this larger fault system is an active structure that accommodates a dip-slip component of motion, giving it significant seismic hazard potential. Consequently, a careful hazard assessment is necessary.

Using GNSS (Global Navigation Satellite System) data collected in Java between 2008 and 2013, Koulali et al. (2017) investigated active faults in the region using an elastic block modeling approach. They concluded that the Baribis-Kendeng thrust is an active fault with an average slip rate of approximately 5 mm/yr. However, their study did not incorporate the Cimandiri fault, which has been well-documented through geological and geophysical investigations (Dardji et al., 1994; Marliyani et al., 2016; Supendi et al., 2018; Arisbaya et al., 2019). By excluding the Cimandiri fault from their modeling process, it is possible that the estimated slip rates along the Baribis-Kendeng thrust, particularly in southern Jakarta, were overestimated.

Furthermore, Gunawan and Widiyantoro (2019) analyzed compressional strain in Java and identified significant evidence of compressional strain along the Cipamingkis fault, Cimandiri fault, and what they proposed as the Jakarta Fault in southern Jakarta. They also

demonstrated that the compressional strain along the Cipamingkis fault, derived from GNSS data collected between 2008 and 2013, was strongly correlated with $M < 5$ earthquakes that occurred from January to July 2018. The compressional zone in southern Jakarta, identified as the Jakarta Fault by Gunawan and Widiyantoro (2019), was estimated using a sparse GNSS network with an average spacing of ~ 30 km.

To obtain a more detailed understanding of the ongoing deformation in southern Jakarta, we have designed a local GNSS network with an average station spacing of 10 km. Using this new network, we aim to provide a more comprehensive analysis of the tectonic processes associated with the Baribis-Kendeng fault, which is further defined as the Jakarta Fault, in southern Jakarta. Specifically, we will estimate the fault slip rate, locking depth, and dip angle. This paper is structured as follows: (1) First, we describe the field GNSS campaign measurements conducted in the region; (2) second, we outline the GNSS data processing methods; (3) third, we explain the modeling procedures used to estimate the fault slip rate and locking depth of the Jakarta Fault; and (4) finally, we discuss the results and their implications.

2. Data And Method

GNSS Data and Processing

The Global Geophysics Research Group at Institut Teknologi Bandung (ITB) conducted a GNSS measurement campaign from 2019 to 2023. The campaign included seven GNSS stations located in Jakarta and its surrounding regions, designated as JKT1 through JKT7. At each station, the GNSS antenna was installed on a concrete benchmark positioned on a rooftop. To complement these data, we also utilized continuous GNSS observations from the InaCORS network—specifically, stations BAKO, CBTU, CJKT, and CTGR—which are operated by the Geospatial Information Agency of Indonesia (e.g., Gunawan et al., 2022). The locations of these stations are depicted in Figure 1.

The collected 30-second RINEX GNSS data were processed using GipsyX software (Bertiger et al., 2020), applying precise point positioning to obtain daily GNSS solutions. A detailed description of the processing workflow is provided in a separate publication (Gunawan et al., 2023). To ensure compatibility with the ITRF2014 reference frame (Altamimi et al., 2016), the analysis incorporated parameters from the Jet Propulsion Laboratory's re-analysis of the IGS14 orbit and clock product. A fiducial-free approach was implemented, involving five iterative steps, with an elevation cut-off angle set at 15° . Additionally, ocean-loading effects were accounted for using parameters from the GOT4.8 model, sourced from the Onsala Space Observatory (<http://holt.oso.chalmers.se/loading/>).

To appropriately interpret the tectonic processes, the daily GNSS solutions should be referenced to a specific tectonic plate or block (Gunawan et al., 2024b). In this study, we employed the Sundaland reference frame as defined in the ITRF2000 framework (Simons et al., 2007). Consequently, we transformed our data from ITRF2014 to ITRF2000 prior to calculating the motion of the Sundaland block. Our results reveal horizontal component errors of approximately 2 mm and vertical component errors of approximately 7 mm. Figure 2 illustrates the GNSS time series data in the Sundaland reference frame for each station. From the time series data, we applied a linear fitting approach to determine the GNSS velocities (Table1; Figure 3).

Modelling Fault Slip Rate

We estimate the slip rate on the fault by fitting a simple 2-D screw dislocation model to the north-south component of the GNSS velocities projected onto a profile perpendicular to the approximately east-west trending fault. Our model setup is shown in Figure 4, which we adapt from Freud and Barnett (1976) and Mallick et al. (2019). For a fault dipping to the south at angle δ from the horizontal and locked to a depth h , the north-south surface velocity, v_x , can be estimated using:

$$v_x = \frac{S}{\pi} \left\{ \frac{\sin \delta - \frac{x}{h} \cos \delta}{1 + \left(\frac{x}{h}\right)^2} + \cos \delta \arctan \frac{x}{h} \right\} + a$$

where S is the fault slip rate and a is a static offset.

We find the best-fit values for each parameter, (S, δ, h, a) , using the Python implementation of the Goodman and Weare (2010) affine-invariant ensemble Markov Chain Monte Carlo (MCMC) sampler called emcee (Foreman-Mackey, 2013), and following the approach of Hussain et al. (2023). Our MCMC sampler explores the parameter space constrained by $0 < S \text{ (mm/yr)} < 15$, $10 < \delta \text{ (degrees)} < 90$, $0 < h \text{ (km)} < 25$, $-10 < a \text{ (mm/yr)} < 10$, assuming a uniform prior probability distribution over each range (Figure 5). We run the MCMC calculation with 32 walkers over 3000 iterations, allowing 500 steps for burn in. This results in 144,000 independent samples from which we estimate the maximum likelihood solution.

3. Results and Discussion

Fault slip rate, locking depth and dip angle

The results of our MCMC calculations are presented in Figure 6. The solid blue line indicates the maximum likelihood solution. However, significant uncertainty surrounds this solution, as highlighted by the shaded region around the line, which corresponds to the 90% confidence range. The posterior distribution also enables us to quantify the uncertainty for each individual parameter. The maximum likelihood solution and the 90% confidence range for each parameter are as follows: slip rate: 3.2 mm/yr (1.2 mm/yr – 5.7 mm/yr), locking depth: 7.2 km (2.6 km – 15.1 km), and fault dip: 63° (46° – 80°).

This study presents a new result for slip rate estimation using a dense GNSS campaign network deployed near the Jakarta Fault. Prior to this work, no studies had utilized such a dense GNSS network in the region. Although Koulali et al. (2017) previously estimated slip rates around the Jakarta Fault, their analysis relied on a regional GNSS network with only two stations located near Jakarta. Our recent analysis, incorporating new campaign data, reveals a slip rate of 3.2 mm/yr, confirming ongoing active deformation along the fault system. This estimate is slightly lower than the previously reported slip rate of 5 mm/yr for the same fault system (e.g., Koulali et al., 2017). The 2017 national seismic hazard map (Indonesian National Center for Earthquake Studies, 2017; Irsyam et al., 2020) notably omitted the Jakarta Fault. The Baribis-Kendeng Fault (the broader structure, which the Jakarta Fault is a part of) has been included in the recent national fault source update (Irsyam et al., 2024). However, its slip behaviour remained uncertain. Characterizing this fault's kinematics is essential for estimating earthquake recurrence and improving seismic hazard analysis, which is critical for updating the new seismic hazard assessment map of Indonesia.

Implication for seismic hazard

The historical seismicity of Jakarta, Indonesia (formerly Batavia), includes a significant earthquake in 1780, which is regarded as one of the most notable seismic events of the 18th century in the region. Dutch colonial records from that period indicate that this earthquake caused substantial damage to infrastructures belonging to the Dutch East India Company in what is now Jakarta's Old Town (Kota Tua) district. The source of this 1780 earthquake is estimated to be associated with the fault system near Jakarta (e.g., Nguyen et al., 2015).

Based on our calculated slip rate and its relationship to historical seismic activity, this fault system has the potential to generate significant earthquakes. By considering the cumulative strain accumulated over approximately 210 years since the last major event and multiplying it by the fault slip rate, we estimate possible displacements of ~0.7 m if an earthquake were to occur. To calculate the geodetic moment uncertainty, we applied the error

propagation method proposed by Gualandi et al. (2017). Based on a fault length of ~50 km, a shear modulus of 30 GPa, a slip rate of 1.2-5.7 mm/yr and a fault depth of 2.6-15.1 km, our result suggests a geodetic moment of $[7.4 \pm 0.6] \times 10^{18}$ N·m, equivalent to M_w between 6.49 and 6.54. The earthquake magnitude is calculated using scaling relations of shear modulus, area and slip (e.g., Kanamori, 2006).

The seismic risk is particularly concerning, as even minor to moderate earthquakes have caused significant damage, especially in Indonesia. For instance, the 2021 M_w 6.2 Mamuju-Majene, Indonesia, earthquake and the 2022 M_w 5.6 Cianjur, Indonesia, earthquake resulted in widespread building collapses (Gunawan et al., 2022; Gunawan et al., 2024b). The implications for the Jakarta metropolitan area could therefore be severe. A major earthquake generated by this fault system could lead to extensive devastation, although this assessment would benefit from updated seismic hazard modeling.

4. Conclusion

In this study, we utilized new GNSS campaign data to estimate the fault slip rate, locking depth, and dip angle of the Jakarta Fault. The fault slip rate was estimated by applying a basic 2-D screw dislocation model to the north-south GNSS velocity components, which were projected onto a profile crossing the approximately east-west oriented fault. Our results reveal a slip rate of 3.2 mm/yr, a locking depth of 7.2 km, and a dip angle of 63°, confirming active deformation along the fault system. Assuming a fault length of 50 km and an earthquake recurrence interval of ~210 years, the next earthquake along this fault could potentially reach a magnitude between 6.49 and 6.54. This study highlights the ongoing deformation along the Jakarta Fault, emphasizing the need for greater attention from stakeholders. Given the potential severity of a seismic event of this magnitude, the implications for the Jakarta region could be catastrophic, necessitating immediate action and updated hazard assessments.

Data and resources

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to in the work reported in this paper.

Author agreement and acknowledgments

All authors agree for this publication. Figures were generated using the Generic Mapping Tool (GMT) software provided by Wessel et al. (2019). This work is partially funded by the Excellent Research of the Institut Teknologi Bandung, and the Indonesia Deposit Insurance Corporation (Lembaga Penjamin Simpanan) under Memorandum of Agreement, Number PKS-3/KPHL/2024 and 842/IT1.B07/KS.00/2024. Ekbal Hussain is supported by the British Geological Survey International NC programme “Geoscience to tackle Global Environmental Challenges,” NE/X006255/1. Ekbal Hussain publishes with permission from the Executive Director of the British Geological Survey.

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Table 1. Velocities at each GNSS station used in this study with respect to the Sundaland reference frame.

Site	Longitude	Latitude	East*	North*	σ_E^*	σ_N^*
BAKO	106.84	-6.49	-0.09	0.12	0.01	0.01
CBTU	107.09	-6.30	-0.16	0.16	0.02	0.01
CJKT	106.88	-6.11	0.02	0.22	0.03	0.01
CJKU	106.84	-6.15	-0.71	-0.30	0.23	0.13
CTGR	106.66	-6.29	-0.06	0.22	0.03	0.02
JKT1	106.77	-6.25	-0.14	0.26	0.12	0.09
JKT2	106.78	-6.32	0.13	0.07	0.04	0.06
JKT3	106.74	-6.37	-0.13	0.09	0.05	0.04
JKT4	106.72	-6.47	-0.23	0.21	0.10	0.07
JKT5	106.92	-6.25	-0.04	0.16	0.02	0.04
JKT6	106.92	-6.32	-0.03	0.10	0.07	0.06
JKT7	106.95	-6.45	-0.11	0.15	0.09	0.08

* in cm/yr

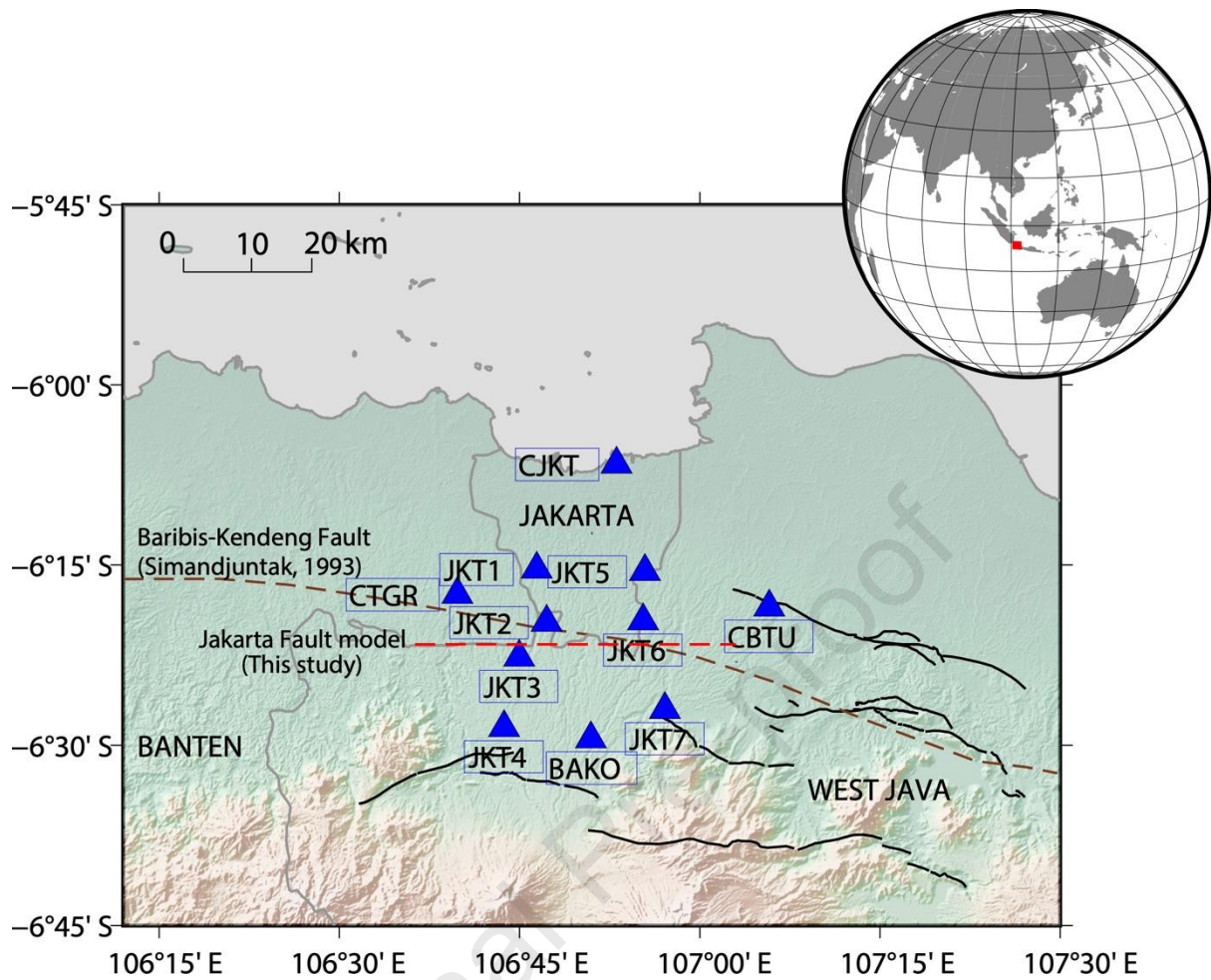


Figure 1. Tectonic setting of the study area. Blue triangles denote the locations of GNSS stations used in this study. Gray lines represent the provincial boundaries of Jakarta, Banten, and West Java. Solid black lines indicate active faults as mapped by Aribowo et al. (2022), while the dashed brown line represents the fault proposed by Simandjuntak (1993). Dashed red line indicate the location of Jakarta Fault used in this study. The inset illustrates a global map, with a red square highlighting the location of this study.

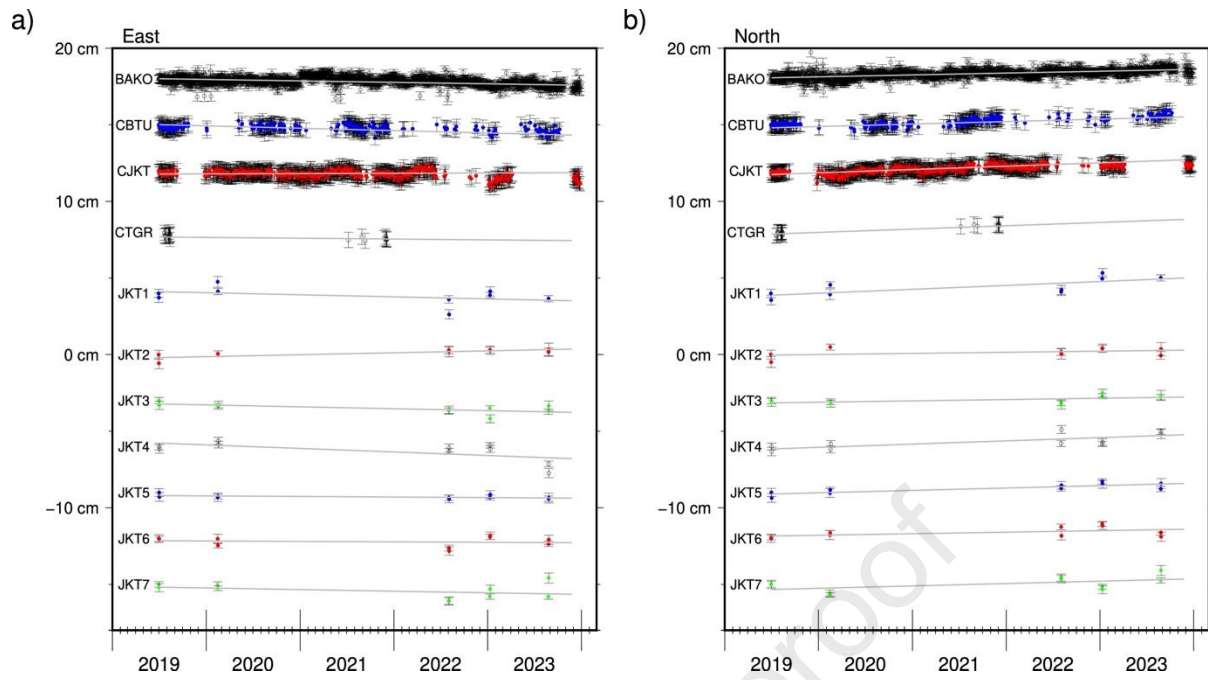


Figure 2. Time series of GNSS data for (a) the East component and (b) the North component from 2019 to 2023. The gray solid lines represent the linear fitting of the GNSS data.

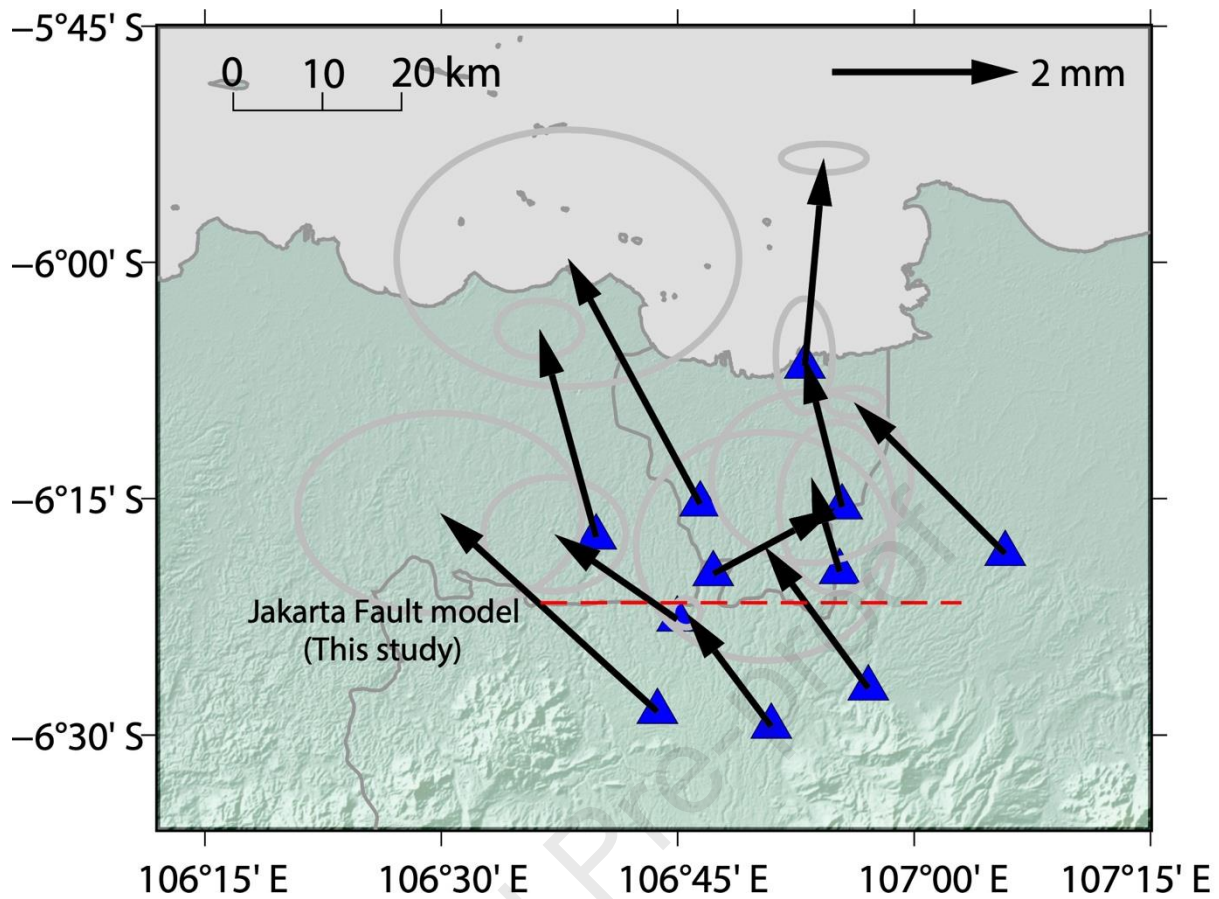


Figure 3. GNSS velocities in the Sundaland reference frame used in this study. Solid gray circles represent data errors (See Figure 1 for a detailed description of the figure legend)

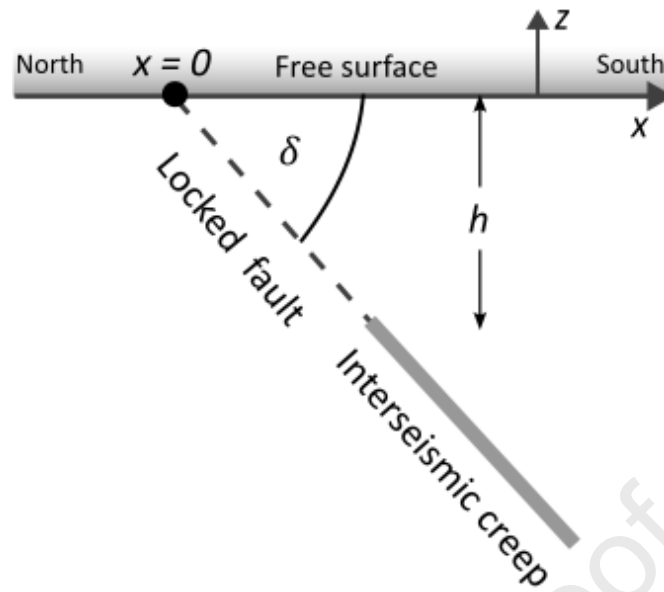


Figure 4. The 2-D dislocation model setup, adapted from Freud and Barnett (1976), for estimating the interseismic slip rate on a dipping fault. The dashed portion of the fault is assumed to be locked (down to depth h), while the solid grey portion slips continuously during the interseismic period. The fault dips in the positive x direction, which in our case is to the south of the fault trace.

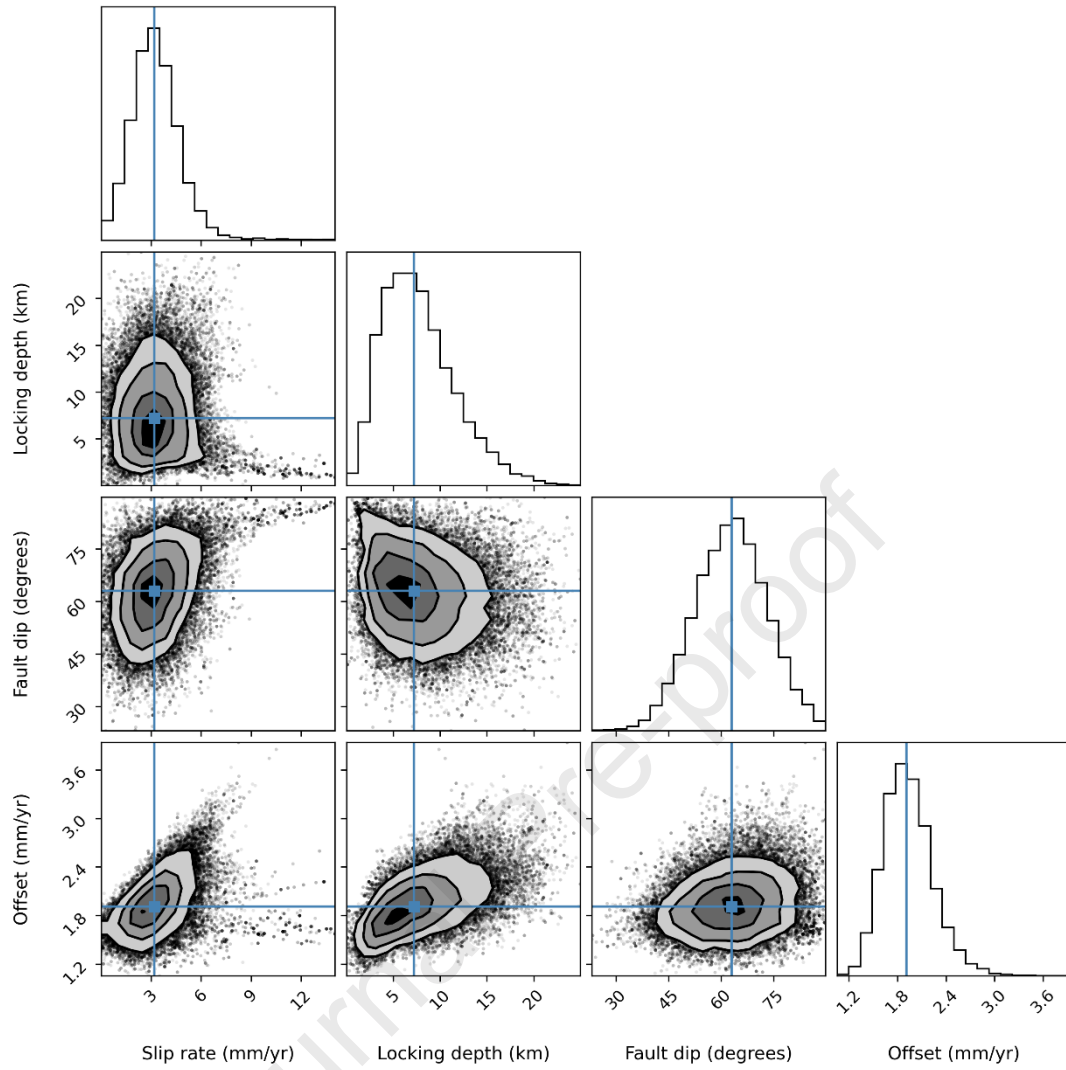


Figure 5. Marginal probability distributions for each model parameter derived from the MCMC samples. The priors for the sampler was constrained by $0 < S \text{ (mm/yr)} < 15$, $10 < \delta \text{ (degrees)} < 90$, $0 < h \text{ (km)} < 25$, $-10 < a \text{ (mm/yr)} < 10$. Results obtained from the MCMC simulations are shown by the black dots and coloured contours. The maximum likelihood estimations are shown by the blue squares and correspond to a fault slip rate of 3.2 mm/yr, a dip angle of 63° , and a locking depth of 7.2 km.

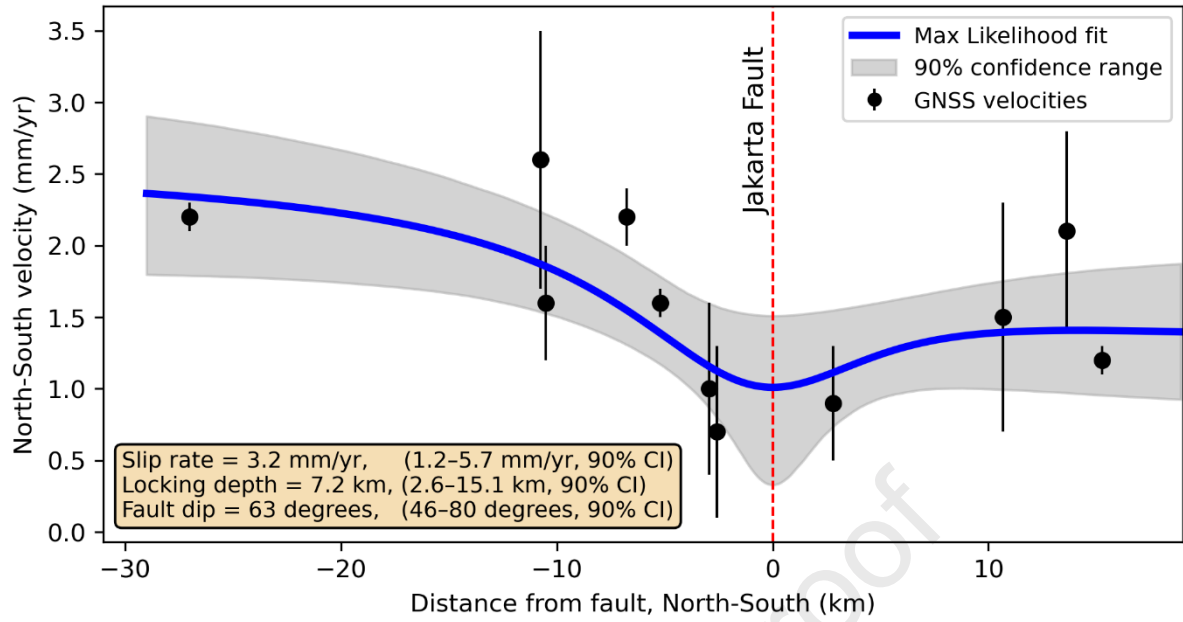


Figure 6. The north-south component of the GNSS velocities projected on a profile perpendicular to the approximately east-west trending Jakarta Fault. In this model setup the fault dips to the south (positive x). The dashed vertical blue line is the location of the fault. The thick blue line is the maximum likelihood solution from our MCMC calculations. The grey shaded zone around this line represents the 90% confidence region. The maximum likelihood solution and corresponding 90% confidence interval of each parameter is given in the inset box.

Declaration of competing interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to in the work reported in this paper.