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**Regional Kinematics of the Banda Arc Transition Zone from
Seismic and Geodetic Constraints**

Hendro Nugroho

Geophysics
Research School of Earth Sciences
College of Science

A thesis submitted for the degree of Doctor of Philosophy at
The Australian National University

Supervisor:
Prof. Meghan S. Miller
Dr. Simon McClusky
Dr. Babak Hejrani
Dr. Sima Mousavi

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DECLARATION

I declare that this thesis is an account of research carried out between August 2018 to September 2025 at The Research School of Earth Science at the Australian National University under the supervision of Professor Meghan S. Miller. The full supervisory board includes Dr. Simon McClusky, Dr. Babak Hejrani, and Dr. Sima Mousavi. The material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

This thesis is a compilation of three original research articles, which are listed below. All co-authors have given their consent to include papers in this thesis.

Article I

Nugroho, H., Hejrani, B., Mousavi, S., Miller, M. S. (2024). Rupture Pattern of 2015 Alor Earthquake Sequence, Indonesia. *Seismological Research Letters*, 95(3), 1632–1645, doi: <https://doi.org/10.1785/0220230185>.

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Article III

Nugroho, H., Miller, M. S., McClusky, S., Hejrani, B., Mousavi, S., Fernandes, R., Soares, E., Jones, F.J.G., Almeida, G.P. Resolving Microplate Kinematics in the Western Banda Arc Using GPS Observations and Multiscale Strain Modeling. The manuscript has been submitted to *Tectonophysics*, An International Journal of Integrated Solid Earth Sciences.

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	Signature	Date
Candidate: Hendro Nugroho		25 August 2025
Main Supervisor Prof. Meghan S. Miller		25 August 2025
Co-Supervisor and Collaborating Author on Article II, III Dr. Simon McClusky		25 August 2025
Co-Supervisor and Collaborating Author on Article I, III Dr. Babak Hejrani		25 August 2025
Co-Supervisor and Collaborating Author on Article I, III Dr. Sima Mousavi		25 August 2025
Collaborating Author on Article II Dr. Phil R. Cummins		25 August 2025
Collaborating Author on Article II Dr. Siyuan Zhao		25 August 2025

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Signed: _____
Hendro Nugroho

Date: 25 August 2025

ABSTRACT

Indonesia and Timor-Leste lie within an active tectonic zone where the Indo-Australian, Pacific, and Sundaland Plates converge, resulting in complex crustal deformation and high seismicity. This study characterizes deformation across the region using broadband seismic waveform data and geodetic observations from the Global Positioning System (GPS).

Seismic data from a temporary 30-station broadband array (YS network) were used to investigate the 2015 Alor earthquake sequence. We computed nine Centroid Moment Tensor (CMT) solutions to describe source mechanisms, using full waveform inversion across multiple frequency bands and velocity models. The analysis included hypocenter relocation, fault plane identification, and rupture direction estimation. These efforts revealed a previously unidentified fault on Alor Island, now interpreted as an active structure contributing to regional deformation and incorporated into subsequent geodetic modeling.

To assess regional plate boundary reorganization, we developed a kinematic block model using over 200 GPS velocities and 492 earthquake slip vectors from the Indonesia–Australia–New Guinea collision zone. The model resolves major block motions and reveals significant variations in slip rates and rotation, particularly across the New Guinea Fold-and-Thrust Belt and the Banda Arc. Elevated residuals in some regions suggest unmodeled micro-blocks or internal strain.

Focusing on the Timor region, we refined the block model to define six micro-blocks based on GPS data, active fault mapping, and strain-rate analysis using a wavelet-based multiscale method. Despite the relatively low misfit in the broader regional model, results indicate that the Timor block undergoes internal deformation and cannot be treated as a single rigid body. These micro-blocks accommodate differential motion and localized strain, underscoring the island’s complex tectonics.

Overall, this integrated geodetic and seismic analysis advances understanding of crustal deformation and active tectonics in the Banda Arc region and informs future seismic hazard assessment.

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Hendro Nugroho

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QUOTATIONS

"Non scholæ sed vitæ discimus. (We do not learn for school but for life.)"

- Lucius Annaeus Seneca
Roman Philosopher, 4 BC – AD 65

"Hold fast to dreams,
For if dreams die
Life is a broken-winged bird,
That cannot fly."

- Langston Hughes

"If I have seen further it is by standing on the shoulders of giants"

- Isaac Newton (1642–1727)

DEDICATION

This thesis work is dedicated to my wife, Nova, who has been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life. This work is also dedicated to my parents, Hartono and Heruni, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

List of Abbreviations

ADBL Adelbert block

AFTB Aure Fold-and-Thrust Belt

ALOS-2 Advanced Land Observing Satellite

ANT Ambient Noise Tomography

ANU Australian National University

AUST Australian Plate

BA Banda Arc

BAND Banda block

BD Banda Detachment

BH Bird's Head

BIG Indonesian Geospatial Information Agency

BMKG Badan Meteorologi dan Geofisika

BRHD Bird's Head block

BS Banda Sea

BSSL Bismarck Sea Seismic Lineation

BTFZ Bewani-Torricelli fault zone

CB Cenderawasih Bay

CCOP Coordinating Committee for Geoscience Programmes in East and Southeast Asia

CEND Cendrawasih Bay block

CMT Centroid Moment Tensor

CTIM Central Timor block

CPS Computer Program in Seismology

DC Double Couple

DI D'Entrecasteaux Islands

DOY Day of the Year

EJAV East Java block

EMAK East Makassar block

ENGH East New Guinea Highland block

EOPs Earth orientation parameters

ETIM East Timor block

FES Finite Element Solution

FBT Flores Back-arc Thrust

FORE Forearc block

GAMIT GNSS Analysis at MIT

GCMT Global Centroid Moment Tensor

GFZ Deutsches Geo Forschungs Zentrum

GLOBK Global Kalman Filter

GMF Global Mapping Function

GMT Generic Mapping Tools

GNSS Global Navigation Satellite System

GPS Global Positioning System

GPT Global Pressure and Temperature

GWB Geoscience Without Borders

HDR Higher Degree Research

HP Huon peninsula

IANGCZ Indonesia–Australia–New Guinea collision zone

IERS International Earth Rotation and Reference Systems Service

IGTL Instituto de Geociências de Timor-Leste (Institute of Geosciences of Timor-Leste)

IGS International GNSS Service

InSAR Interferometric Synthetic Aperture Radar

IPG Instituto do Petróleo e Geologia (The Institute of Petroleum and Geology)

IRIS-DMC Incorporated Research Institutions for Seismology Data Management Center

ISC International Seismological Centre

ITRF International Terrestrial Reference Frame

KSZ Kawa Shear Zone

L1 GPS signal at 1575.42 MHz

L2 GPS signal at 1227.60 MHz

LC Ionosphere-free linear combination of L1 and L2

LFTB Lengguru Fold-and-Thrust Belt

LFZ Lagaip fault zone

LG Geometry-free linear combination of L1 and L2

LiDAR Light Detection and Ranging

LLFZ Lowlands Fault

MADB Mamberamo deformation zone block

MCS Multi-Channel reflection Seismic

MDZ Mamberamo deformation zone

MF Masupu Fault

MIT Massachusetts Institute of Technology

MS Molucca Sea

MT Moresby Trough

NBBL North Bismarck block

NBT New Britain Trench

NEIC National Earthquake Information Center

NETI North-and-East of Timor block

NGFTB New Guinea Fold-and-Thrust Belt

NIED National Research Institute for Earth Science and Disaster Resilience

NISAR NASA–ISRO Synthetic Aperture Radar

NRMS Normalized Root Mean Square

NSF National Science Foundation

NTIM North Timor block

OSFZ Owen Stanley fault zone

P-code Precision code used in military GPS signals

PDF Probability Density Function

PFZ Paniai fault zone

PP Papuan peninsula

PTFB Papuan thrust-and-fold belt

PACI Pacific Plate

PNG Papua New Guinea

PPBL Papuan Peninsula block

PREM Preliminary Reference Earth Model

RINEX Receiver INdependent EXchange

RFZ Ransiki fault zone

RMFZ Ramu-Markham fault zone

RMS Root Mean Squared

RCMT Regional Centroid Moment Tensor

SAC Seismic Analysis Code

SBBL South Bismarck block

SBS South Bismarck Sea

SEED Standard for the Exchange of Earthquake Data

SERA Seram block

SF Semaui Fault

SFZ Sorong fault zone

SLAR Side Looking Airborne Radar

SLT Selayar Trough

SOPAC	Scripps Orbit and Permanent Array Center
ST	Seram Trench
STIM	South Timor block
SUMB	Sumba block
SUND	Sunda block
TABL	Tarera-Adiuna fault zone block
TAFZ	Tarera-Aiduna fault zone
TEQC	Translation, Editing, and Quality Check
TFZ	Tahin fault zone
TI	Timor
TIMO	Timor block
TT	Trobriand Trough
SWIFT	Source parameter determination based on Waveform Inversion of Fourier Transformed seismograms)
UNAVCO	University NAVSTAR Consortium
USGS	United States Geological Survey
VDoHS	Vertical Derivatives of Horizontal Stress
Vs	shear-wave velocity
WDBL	Woodlark block
WF	Walanae Fault
WL	Wide-Lane (L1–L2 carrier phase combination used in GPS)
WMAK	West Makassar block
WNGH	West New Guinea Highland block
WR	Woodlark Rift
WRMS	Weight Root Mean Squared
WT	Weyland Thrust
WTIM	West Timor block
YAPE	Yapen block
YFZ	Yapen fault zone

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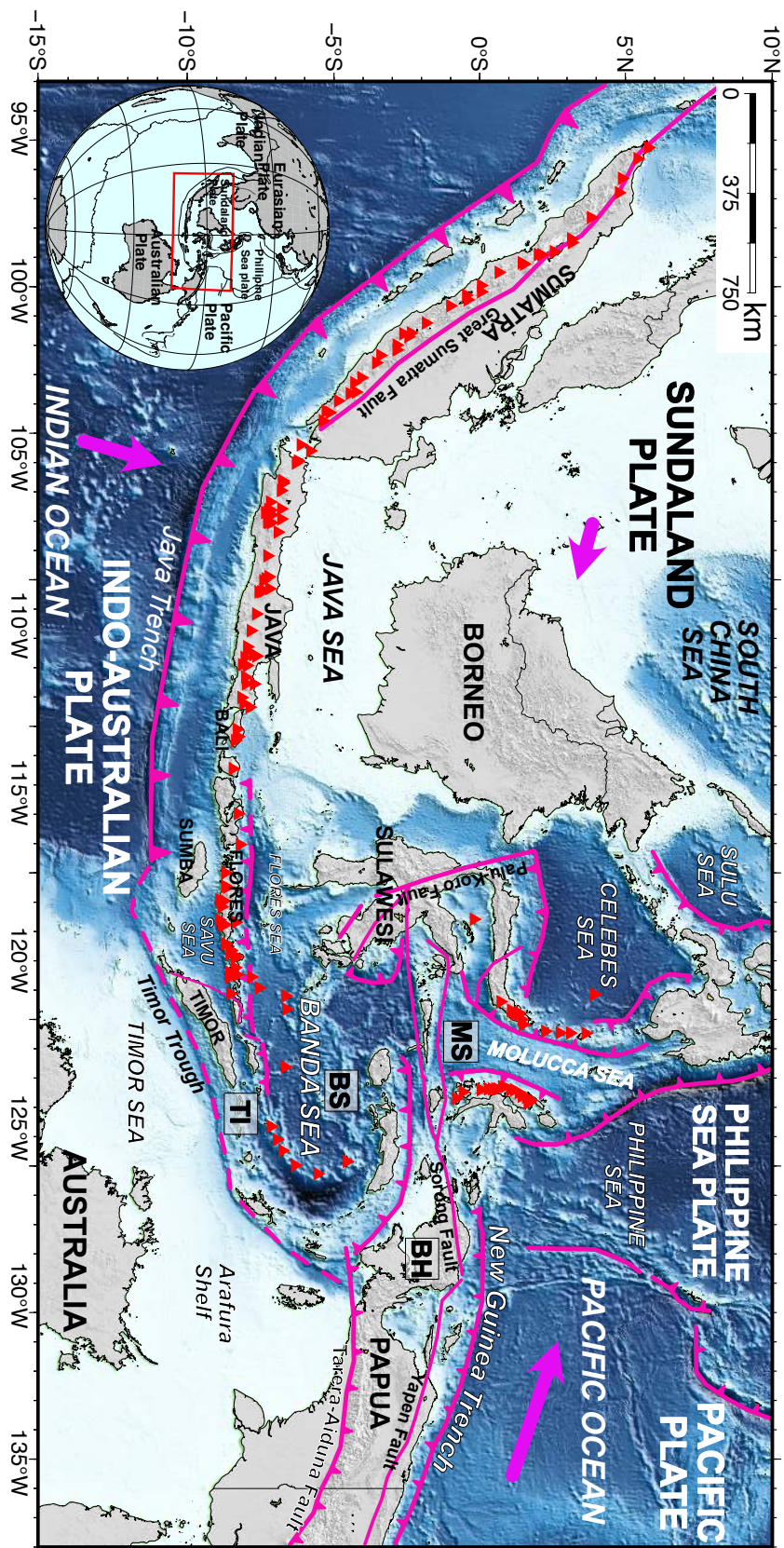
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Introduction

1.1 Deformation study in Banda region

Indonesia and Timor-Leste are located in an active tectonic zone where three major plates—the Sundaland Plate, the Indo-Australian Plate, and the Pacific Plate (Figure 1.1)—converge, resulting in a complex configuration, interaction, and movement of these plates. The Indo-Australian Plate moves north-northeast at a rate of about 70 mm/yr (DeMets et al., 2010; Genrich et al., 1996; Bock et al., 2003; Nugroho et al., 2009). Its oceanic part subducts beneath the Sundaland Plate in the west, imprinting on the ocean topography as the Java trench. The orogenic processes build a chain of volcanoes along the arc, which extends over 5,000 km from the north of Sumatra to the Lesser Sunda Islands (Figure 1.1). The Sundaland Plate itself moves slowly from the west-northwest to the east-southeast at a rate of about 30 mm/yr (Bird, 2003). In eastern Indonesia, specifically in the Banda Arc, the oceanic plate is consumed in the subduction processes, and now the less dense Australian continental margin is colliding with the islands arc in the region. The plate interaction complexity is further compounded by the Pacific Plate moving west-northwest at a rate of about 80 mm/yr (Stevens et al., 2002), contributing to the intense tectonic activity in this region, which leads to significant deformation and frequent earthquakes, making them significant sources of hazards in the region.

As a result of the tectonic evolution processes, major plates break into smaller plates or blocks, which can further fragment into micro-plates. This process creates a complex and dynamic tectonic environment. Bird (2003) identified several micro-



plates or blocks in the region, including the Molucca Sea (MS), the Banda Sea (BS), Timor (TI), and Bird's Head (BH) (see Figure 1.1). The long process of plate reorganization manifests through a series of dynamic crustal deformation and tectonic earthquakes, characterized by sudden slips on faults that generate seismic waves across observable frequency bands detectable with seismometers. These earthquakes generate both static and dynamic displacements.

While GPS or geodetic instruments are essential for measuring the static motions, seismometers can record the dynamic ones. Through a temporary instrument deployment from 2014 to 2019 in the region (Miller et al., 2016), approximately 20,000 earthquakes were cataloged (Jiang et al., 2022). Despite many surface deformation signals, such as those along plate boundary fault systems, being well expressed, the ruptures and mechanisms of the crustal earthquakes often remain invisible at the surface level. However, the source mechanism of an earthquake, including the orientation and type of faulting—such as normal, reverse, strike-slip, or oblique—along with the fault plane's strike, dip, and slip direction, can be determined using waveform data and the Centroid Moment Tensor (CMT) inversion method (Dziwowski et al., 1981). CMT inversion offers robust constraints on the seismic source mechanism, particularly for events lacking clear surface expression.

To complement seismic analyses, geodetic methods such as GPS have become essential in understanding long-term crustal deformation. Currently GPS has become a common tool to understand the spatial pattern of crustal deformation in a region both through derived velocity vectors and block models (Matsu'ura et al., 1986; McCaffrey et al., 2002; Meade and Loveless, 2009; Meade and Hager, 2005). The method is based on the idea that the crust or lithosphere is comprised of discrete bounded blocks laterally, but a stress-free region at the base (asthenosphere). While the blocks rotate on the Earth's surface at an angular velocity (about an Euler pole), frictional interactions between blocks describe their lateral boundaries. These interactions cause elastic strains to build along the block boundaries. GPS observations contain infor-

mation about the angular velocities of the blocks, slip rates of their bounding faults, and the frictional properties of the bounding faults.

These data can be used to constrain block models, through which interseismic deformation at various scales can be characterized by focusing on slip at fault boundaries. However, to capture deformation that is not confined to block boundaries, a wavelet-based multiscale approach ([Tape et al., 2009](#)) offers a continuous, multi-scale analysis of distributed deformation from the derived strain-rate field. These two methods provide a comprehensive understanding of deformation patterns in the region.

1.2 Research Goal and Key Questions

The primary objective of this research is to gain a deeper understanding of crustal deformation in the Banda Arc region by analyzing local and regional seismic as well as geodetic data to gain valuable insights into the plates interaction and deformation. Questions we are trying to answer from this research are as follows. First, considering the numbers of micro-plate boundaries proposed ([Audley-Charles, 1975, 2004](#); [Bird, 2003](#); [Genrich et al., 1996](#); [Harris et al., 2009](#); [Nugroho et al., 2009](#); [Pubellier et al., 2008](#); [Müller et al., 2008](#); [Koulali et al., 2016](#)), what is the current state of plate boundary reorganization on a broad scale, particularly the young collisional complex in the western Banda Arc? How does deformation manifest in the Timor block, as indicated by [GPS](#) data and local moment tensor solutions? What insights do we gain into the internal deformation of the Timor block, particularly on Timor Island? To what extent is the Timor Trough actively involved in these processes? Additionally, how do seismic data describe deformation patterns in the region?

To address the questions and to gain insights into deformation using seismic data, we employed the moment tensor inversion method to calculate the Centroid Moment Tensor ([CMT](#)) solutions for the 2015 Alor earthquake sequence leveraging the seismic data from a temporary deployment in eastern Indonesia from 2014 to

2019 (Miller et al., 2016). The CMT were calculated through a 4D grid search (Hejrani et al., 2017) using local 1D Earth velocity models specific for the Alor region. The moment tensor components were resolved using least squares methods (Kikuchi and Kanamori, 1991), and data fitting following Hejrani et al. (2017). We use the solution to identify the fault plane and rupture direction, which improves seismic hazard assessments of the region. The identified fault might represent a block boundary in the region, shedding light on the current state of deformation.

Furthermore, block models were constructed by incorporating GPS observation data, slip vectors derived from centroid moment tensor solutions, and mapped faults of the region. The models were developed to grasp the extensive and localized deformation occurring in Indonesia, Australia, Timor-Leste, and Papua New Guinea, including the internal deformation of the Timor block. In this case, we utilized GPS data that previously published, as well as unpublished legacy GPS campaign data, and also GPS data collected from campaign surveys conducted in 2014, 2018, and 2019.

1.3 Thesis Outline

This thesis work is divided into two main components. First, study of source mechanism through the Centroid Moment Tensor (CMT) Inversion of 2015 Alor earthquake sequence presented in Chapter 3. Second, block modelling of the Banda region utilizing Global Positioning System (GPS) data presented in Chapter 4 and 5.

The overview of Chapter 3-5 is as follows:

- Chapter 3 investigates the source mechanisms of 2015 Alor Earthquake Sequence in Indonesia through centroid moment tensor inversion. This method leverages seismic data recordings from a temporary array of 30 broadband instruments spread across the Banda Arc region. The inversion process employs a 1D model specifically developed for the region. Based on the Centroid Moment Tensor (CMT) inversion results and relocated hypocentres, the fault plane

of the largest foreshock and the main shock are determined through a probabilistic framework approach. Subsequently, the rupture pattern of the 2015 Alor earthquake sequence is examined based on the results and the distribution of aftershocks.

- Chapter 4 introduces a comprehensive kinematic model encompassing the Indonesia, Australia, and New Guinea subduction and collision zone. The model is composed of 23 elastic blocks, with estimates provided for both rotation and block boundary slip rates.
- Chapter 5 presents a comprehensive view of the deformation patterns in the Banda Arc region using both kinematic block modeling and spherical wavelet methods. The analysis is based on GPS observation data collected over 15 years from Timor-Leste and the surrounding region.

1.4 Publications

Chapter 3 and Chapter 4 have been published, and Chapter 5 has been submitted to the peer-reviewed journal *Tectonophysics*.

- **Chapter 3:** Nugroho, H., Hejrani, B., Mousavi, S., Miller, M. S. (2024). Rupture Pattern of 2015 Alor Earthquake Sequence, Indonesia. *Seismological Research Letters*, 95(3), 1632–1645, doi: <https://doi.org/10.1785/0220230185>.
- **Chapter 4:** Zhao, S., McClusky, S., Cummins, P. R., Miller, M. S., & Nugroho, H. (2023). New Insights Into Crustal Deformation of the Indonesia–Australia–New Guinea Collision Zone From a Broad-Scale Kinematic Model. *Journal of Geophysical Research: Solid Earth*, 128(2), e2022JB024810, doi: <https://doi.org/10.1029/2022JB024810>
- **Chapter 5:** Nugroho, H., Miller, M. S., Hejrani, B., Mousavi, S., McClusky, S., Fernandes, R., Soares, E., Jones, F.J.G., Almeida, G.P. (2024). Resolving Mi-

croplate Kinematics in the Western Banda Arc Using GPS Observations and Multiscale Strain Modeling. *The manuscript has been submitted to Tectonophysics.*

Background

The Earth's crust is in a constant state of motion, driven by the interplay of tectonic forces and geological processes. This motion can manifest as deformation, which includes various forms of displacement, strain, and seismic activity. Understanding the dynamics of crustal deformation is of paramount importance for various reasons, including accurately assessing seismic hazards, predicting earthquake occurrences, and comprehending the geological processes shaping the Earth's surface.

Global Positioning System ([GPS](#)) and seismic data are two of the most valuable tools for characterizing and quantifying deformation within a region. [GPS](#) technology has revolutionized crustal deformation monitoring and measurement with an unprecedented level of accuracy for over three decades (e.g., [Hager et al., 1991](#); [Tregoning et al., 1994](#); [Sagiya et al., 2000](#); [Simons et al., 2007](#); [Koulali et al., 2016](#); [Zhao et al., 2023](#)). Continuous [GPS](#) data can achieve accuracy levels on the order of millimeters (e.g., [Altiner, 1999](#)). The accuracy and error budgets have undergone thorough review and discussion (e.g., [Li et al., 2023](#); [Bock and Melgar, 2016](#); [Teunissen and Montenbruck, 2017](#)).

While [GPS](#) data offer precise measurements of surface movements, seismic data, collected from seismometers (ground motion recording instruments) and seismic networks (coordinated arrays of these instruments), play a crucial role in understanding the dynamic behavior of the Earth's crust. Seismic waves generated by earthquakes and other sources propagate through the Earth, carrying information about subsurface structures and the forces that drive deformation. Analyzing seismic data allows

us to characterize sudden and impulsive deformations caused by earthquakes. Moreover, it provides insights into earthquake source mechanisms (e.g., [Udías, 1991](#); [Udías et al., 2014](#)), fault geometry and orientation (e.g., [Aki and Richards, 1980](#); [Hardebeck and Shearer, 2003](#)), magnitude (e.g., [Kanamori, 1977](#); [Hanks and Kanamori, 1979](#); [Das et al., 2019](#)), distribution of seismic activity (including rupture patterns) (e.g., [Mai and Beroza, 2000](#); [Shearer et al., 2005](#)), and ultimately help in understanding the mechanisms responsible for crustal deformation (e.g., [Matsuzawa et al., 2021](#); [Avouac, 2015](#)).

To further investigate the mechanisms driving crustal deformation, [CMT](#) inversion ([Dziewoński et al., 1981](#)) is widely used to determine the source parameters of earthquakes, including fault orientation, slip direction, and moment magnitude. [CMT](#) solutions, obtained through inversion of long-period seismic waveform, provide valuable constraints on the geometry and kinematics of faulting during seismic events. This method enhances our understanding of stress accumulation and release in the lithosphere and helps link observed seismicity to underlying tectonic structures.

In contrast, [GPS](#) data capture interseismic strain accumulation and the plate motions, while [CMT](#) data represent the coseismic response. Integrating these datasets allows for the development of kinematic block models, which quantify relative motion between crustal blocks and estimate slip rates along block-bounding faults.

In this research, we focus on investigating the 2015 Alor earthquake sequence in Indonesia by calculating the [CMT](#) solutions for nine of the earthquakes with $M_w \geq 3.9$, which occurred between November 2015 and March 2016 using records from a temporary array of 30 broadband instruments in eastern Indonesia and Timor-Leste (YS network) ([Miller et al., 2016](#)). We use these results, along with other [CMT](#) solutions in the region (i.e., [Dziewoński et al., 1981](#); [Ekström et al., 2012](#)), to develop an elastic block model and apply spherical wavelet-based strain-rate estimation. With this integrated approach, we aim to resolve both discrete block rotations and dis-

tributed deformation within the Timor Block, thereby improving the characterization of active tectonics and the assessment of seismic hazards in this deforming region.

2.1 Data and Fieldwork

We used three-component broadband data recorded by the YS network to perform waveform modeling and picking P- and S- arrivals for our calculation of [CMT](#) solutions. These broadband instruments are capable of capturing ground motion over a wide frequency range, allowing detailed analysis of both low-frequency and high-frequency waveforms. Waveform modeling involves fitting synthetic seismograms, generated using a specified Earth model and source parameters, to the observed waveforms recorded at multiple stations.

For waveform modeling, we cut windows of 150 s from the origin time, removed the mean and trend, corrected for instrument response and downsampled to 4 Hz. We filtered the data at the frequency band 0.05-0.08 Hz (12.5-20 s). We applied the same sampling and filter to the synthetic data. At this stage, we also visually inspected the seismograms for any clipped waveforms or noisy data. We picked P-wave arrivals on vertical components filtered around 1 Hz (0.5-2 Hz, corresponding to periods of 2-0.5 s) and S-wave arrivals on the transverse components filtered at 0.1-0.5 Hz (2-10 s).

In addition to seismic waveform data that we processed and analyzed for our [CMT](#) inversion, we also utilized [GPS](#) data previously published (e.g., [Koulali et al., 2016](#); [Zhao et al., 2023](#)), as well as unpublished legacy [GPS](#) campaign data for our block modeling. We also conducted [GPS](#) campaign surveys in Timor-Leste at three different points in time: once in 2018 and twice in 2019 (see Table [C.5](#) and [C.6](#)).

We reprocessed [GPS](#) observations collected from 28 campaign stations located in West New Guinea and acquired two new [GPS](#) data from the stations at Timor Island ([McCaffrey, 2002, 2005](#)). The reprocessed data were collected from 2002 to 2004 and processed using the GNSS Analysis at MIT ([GAMIT](#))/ Global Kalman Filter ([GLOBK](#))

software suite (Herring et al., 2015a,b). The GPS sites were observed with three different antenna and receiver combinations: Trimble Global Navigation Satellite System (GNSS) Choke-Ring Antenna/Trimble 4000 SSI, Trimble Zephyr Geodetic GNSS Antenna/Trimble 5700, and Ashtech Geodetic IV GNSS Antenna/Ashtech UZ-12. In East Timor, new GPS observations from the stations DILI and SAME were processed. The DILI station is a semi-permanent station occupied from 2018 to 2019. The SAME station is a campaign station that has been surveyed in 2005, 2018, and 2019. Both stations were occupied using Trimble Zephyr Geodetic GNSS Antenna/Trimble 5700.

These and other GPS data contribute to the Timor block model by constraining block rotations and fault slip rates, while a wavelet-based multiscale method is used in parallel to capture distributed deformation beyond block boundaries. This analysis utilises a combination of data from permanent networks obtained from Indonesian Geospatial Information Agency (BIG) and the International GNSS Service network, along with data from a semi-permanent station installed in Dili, as well as legacy campaign data from 2005 that was previously unpublished, and new data from 2014 collected during a LiDAR survey project in 2014. In addition, we used GPS data obtained from campaign survey conducted in 2018 and 2019 in Timor-Leste. We also utilised earthquake slip vectors, which are useful to constrain the azimuth of block motions and the Euler pole of each block (Aki and Richards, 1980; DeMets et al., 1990, 1994; Koulali et al., 2015, 2016; Tregoning and McQueen, 2001; Zhao et al., 2023). Except for the slip vector of the $M_w 6.2$ of Alor earthquake (Figure 5.1a), we derived the slip vectors from earthquake focal mechanisms in the GCMT catalog (Dziewoński et al., 1981; Ekström et al., 2012) for events with $M_w > 5.5$ occurring between 1976 and 2023 and at depth shallower than 70 km, a threshold selected to capture upper-plate and shallow interface seismicity relevant to Banda Arc deformation while excluding deeper intraslab processes.

The data and fieldwork Section 2.1 outlined the collection and processing of both seismic and geodetic datasets, which serve as the basis for the subsequent analyses.

In the next section, we detail the methodology of [CMT](#) inversion to processed seismic waveforms in order to characterize the source mechanisms of the 2015 Alor earthquake sequence in Indonesia. This is followed by deformation modeling approaches, including kinematic block modeling and a spherical wavelet method, which are both based on [GPS](#) observation data (Section 2.3).

2.2 Centroid Moment Tensor Inversion

Seismic moment tensor estimation is the basis for quantifying the earthquake sources in our region of interest. Calculation of seismic moment tensor can be done by several approaches, including the utilising amplitudes of seismic waves ([Vavryčuk and Kühn, 2012](#); [Godano et al., 2011](#)), S/P amplitude ratio ([Miller et al., 1998](#); [Hardebeck and Shearer, 2003](#)), and full waveforms ([Dziewoński et al., 1981](#); [Sipkin, 1986](#); [Kikuchi and Kanamori, 1991](#); [Šílený et al., 1992](#)). The last approach is a widely used, and it is applicable on all scales of earthquake magnitudes.

As its application continues to grow, the increasing number of both permanent and temporary seismic networks, has significantly increased the number of waveforms recorded at local-to-regional distances. This abundance of regional waveform data has enabled more detailed modeling, which is commonly used not only to provide a good constraint in determination of source mechanism, magnitude, and depth accuracy, but also contribute to estimate faulting parameters of small-to-moderate earthquakes and evaluate stress and strain patterns. This information will help understanding local and regional tectonic features in the study area, especially, for deformation study, where only small events are available.

At the global scale, for about four decades, the [GCMT](#) Project ([Dziewoński et al., 1981](#); [Ekström et al., 2012](#)) routinely estimates centroid moment tensor for medium to large earthquakes based on broadband seismic data from global networks. However, using the [GCMT](#) database to study deformation in the Banda Arc region results in poorly resolved centroid locations. For example, [Hjörleifsdóttir and Ekström \(2010\)](#)

reported lateral and depth discrepancies of tens of kilometers due to the effects of Earth's 3D structure on [GCMT](#) solutions. Similarly, [Nakano et al. \(2010\)](#) identified a systematic deviation of [GCMT](#) source locations toward the Pacific Ocean.

Most of moment tensor solutions in Banda region were calculated not only by using teleseismic data, but also using 1D global Earth velocity models such as [PREM](#) ([Dziewoński and Anderson, 1981](#)) or Ak135 ([Kennett et al., 1995](#)). At regional scale, [Nakano et al. \(2010\)](#) generated centroid moment tensor catalogue for Indonesia (In-aCMT) from 500 events with magnitude range from 4.5 to 8.3 occurred between 2006 and 2009. They used the data obtained from seismic network operated by National Research Institute for Earth Science and Disaster Resilience ([NIED](#)), Deutsches Geo Forschungs Zentrum ([GFZ](#)), and Badan Meteorologi dan Geofisika ([BMKG](#)) from stations located in Indonesia only. The inversion was done using waveform inversion methods they developed ([Nakano et al., 2008](#)) called [SWIFT](#) ([S](#)ource parameter [d](#)eterminations based on [W](#)aveform [I](#)nversion of [F](#)ourier [T](#)ransformed seismograms), which solved the problem in the frequency domain. The source centroid location is estimated using a spatial grid search. A band-pass filter with a frequency range of 0.01–0.02 Hz (50–100 s) was employed, with a sampling frequency of 0.5 Hz (2 s). For estimated earthquake magnitudes greater than 7, the inversion was rerun using passband extended to 0.005 Hz (200 s). Initial hypocentre locations provided by [GFZ](#) were used in an adaptive grid search scheme. Green's functions were synthesized using the discrete wavenumber method ([Bouchon, 1979](#)) using a standard Earth model Ak135 ([Kennett et al., 1995](#)).

Starting in 2014, 30 broadband seismometers were deployed across the Banda Arc-Continental collision zone (Figure 2.1) with an array named YS ([Miller et al., 2016](#)) helping to fill gaps in the seismic network and significantly improve spatial resolution in the region. The availability of data from this network provides an opportunity to enhance the detection of small-magnitude earthquakes and to develop local 1D and 3D velocity models specifically calibrated for the Banda arc-continental

collision zones. Incorporating local waveform data and region-specific velocity models into the [CMT](#) inversion improves the resolution of source parameters, including focal depth, fault orientation, and moment magnitude. These improvements provide more reliable constraints on faulting mechanisms and stress orientations, contributing to a deeper understanding of the complex tectonic processes associated with the Banda Arc–continental collision.

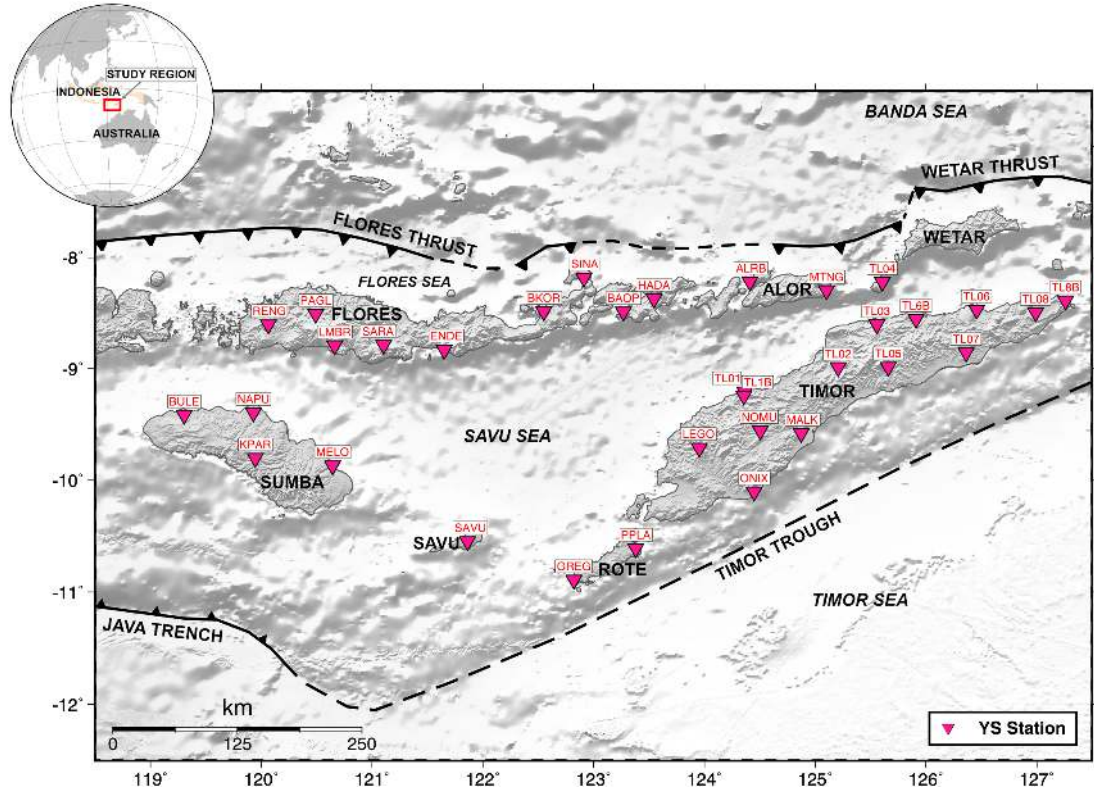


Figure 2.1: A map is showing the thirty seismic stations of YS seismic network in Banda arc region. Three stations in Timor Island had been relocated: TL01 to TL1B, TL06 to TL6B, and TL08 to TL8B. Tambolaka [BULE] stations was destroyed by fire in early 2018.

2.2.1 The Inversion Methodology

In this study, we used the MTINV5 code that is used to produce a regional [CMT](#) catalogue for Papua New Guinea ([PNG](#)) and the Solomon Islands ([Hejrani et al., 2017](#)) to apply moment tensor inversion techniques and to produce moment tensor solution

from regional data and compare the results with the [GCMT](#) catalogue. We determined the source mechanisms of the events of the 2015 Alor earthquake sequence with magnitude ≥ 4.5 M_w and depth ≤ 50 km detected by at least 6 seismometers in the YS network, including both events that are catalogued in [GCMT](#) and those that are not catalogued in their database.

A general outline of the waveform inversion procedure consists of three main steps: (1) data acquisition and preprocessing, (2) computation of synthetic Green's functions, and (3) inversion. In the first step, the waveform data are inspected to ensure good signal-to-noise ratios, absence of clipping, and adequate azimuthal coverage. The records are then detrended and demeaned, instrument responses are removed, and high-frequency noise is suppressed using appropriate low-pass filtering. The second step involves calculating synthetic Green's functions based on the assumed Earth model, source location, and receiver geometry. In the final step, selected observed waveforms are compared with synthetics, and the inversion is performed by minimizing waveform misfits to estimate the source parameters. Model performance is evaluated using waveform fit quality quantified by variance reduction and source-type stability assessed by the Double Couple ([DC](#)) percentage, complemented by residual analysis to identify systematic waveform misfits.

There are three factors affecting the resolution and stability of moment tensor inversions. They are: poor velocity model ([Romanowicz, 1993](#); [Cesca et al., 2006](#); [Šílený, 2004](#)), noisy seismic data ([Sokos and Zahradník, 2013](#); [Šílený et al., 1996](#)), and limited azimuthal coverage ([Cesca et al., 2006](#); [Ford et al., 2010](#); [Vera Rodriguez et al., 2011](#)). Each of these factors has been considered and addressed to ensure robust and reliable inversion outcomes.

Seismic stations record ground motions generated by waves that propagate through the Earth from a seismic source. These recorded signals, typically in velocity, contain a combination of information related to the source mechanism, the Earth structure, and the displacement occurred at the source location x due to the

impulsive force (f_j) at x_0 . In theory, the ground motion can be expressed as a convolution of the source with the Earth's Green's function (see [Aki and Richards, 2002](#)), as follows:

$$u_i(\mathbf{x}, t) = G_{ij}(\mathbf{x}, t; \mathbf{x}_0, t_0) * f_j(\mathbf{x}_0, t_0) \quad (2.1)$$

where u_i represents the theoretical displacement at location $\mathbf{x}$ (in practice, Green's functions can be differentiated or integrated to match the observed velocity or acceleration), f_j is the source force vector, and G_{ij} is the elastodynamic Green's function from the source $\mathbf{x}_0$ to the observation point $\mathbf{x}$. Convolution over time is represented by $*$.

Although $u(\mathbf{x}, t)$ can be a complicated function of the Earth's seismic velocity and density structure, for each $f(\mathbf{x}_0, t_0)$, there is a unique $u(t)$ that describes the Earth's response model. With availability of an accurate Earth's structure model, it could be computed.

For a point source, elastic displacements outside the focal region u_i in terms of M_{kj} and the corresponding Green function is expressed ([Udias and Bufo, 2017](#)):

$$u_i = M_{kj} * G_{ik,j} \quad (2.2)$$

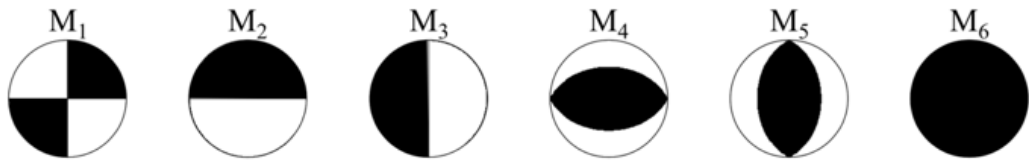


Figure 2.2: The six elementary moment tensors used in the inversion of full moment tensors.

where M_{kj} represents a couple of opposite forces along $\hat{j}$ with infinitesimal separation in the $\hat{k}$ direction. The general moment tensor M can be represented as a linear combination of a set of elementary MTs, M_n ([Kikuchi and Kanamori, 1991](#); [Zahradnik](#)

et al., 2005) as written in equation 2.6 and Figure 2.2. Using the set of MTs allow certain solutions, such as pure deviatoric or pure double couple, to be obtained from each subgroup of the six elementary MTs. For example, pure deviatoric is represented by M_1 – M_5 .

A seismogram can be expressed as a linear combination of six elementary seismograms using a simplified equation of matrix form for real data (Hejrani et al., 2017):

$$U = EA \quad (2.3)$$

where U is the vector of observed data (displacement amplitudes from three-component seismic stations), A is the vector of six MT coefficients to be determined, and E is the matrix of elementary seismograms (with size of 6 by length of U). The least squares method is used to estimate the vector of the coefficients, A (Hejrani et al., 2017):

$$(E^T E)^{-1} (E^T U) = A_{est.} \quad (2.4)$$

where $A_{est.}$ is the estimation vector of coefficients A . The six independent components of the moment tensor can then be calculated from the estimated a_i coefficients:

$$A_{est.} = \begin{bmatrix} -a_4 + a_6 & a_1 & a_2 \\ a_1 & -a_5 + a_6 & -a_3 \\ a_2 & -a_3 & a_4 + a_5 + a_6 \end{bmatrix} \quad (2.5)$$

Assuming that the earthquakes in this study are of a tectonic origin, the volumetric component, M_6 , will not be considered and calculate the deviatoric moment tensor, represented by the first five bases M_1 to M_5 with a_6 equal to zero.

Moment tensor inversion will be done using MTINV5 (Hejrani et al., 2017), a comprehensive MATLAB package to conduct the inversion. Conversion of Standard for the Exchange of Earthquake Data (SEED) files to Seismic Analysis Code (SAC)

and removal of instrument response data is done using the code by invoking IRIS RDSEED (<http://www.iris.edu>) to read, extract, and convert the full SEED data into SAC format and creates many folders associated with data from each station. The following step is generation of the six elementary seismograms following Kikuchi and Kanamori (1991) algorithm in which the moment tensor is decomposed into elementary double-couple sources and an explosive source. The moment tensor, M_{kj} , is represented by a linear combination of $N_e = 6$ elementary moment tensors M_n , where a_n is the coefficients:

$$M_{kj} = \sum_{n=1}^{N_e} a_n M_n \quad (2.6)$$

with

$$\begin{aligned} M_1: \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}; M_2: \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}; M_3: \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{bmatrix} \\ M_4: \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}; M_5: \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; M_6: \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (2.7)$$

The M_1 represent strike-slip faults; M_2 and M_3 represent dip-slip faults on vertical planes striking E-W and N-S, respectively; M_4 and M_5 represents a 45° dip-slip fault. The M_6 represents an isotropic source radiating energy equally into all directions (i.e., an explosion) (Figure 2.2).

One of the most important steps in the inversion process is computing Green's functions. The function represents the impulse response of the medium between source and receiver and thus contains the various wave propagation effects through the medium from source to receiver including energy losses through reflection and

transmission at seismic discontinuities, anelastic absorption and geometrical spreading. We compute the Green's function using wavenumber integration techniques to generate synthetic seismograms implemented in Computer Program in Seismology (CPS) (Herrmann, 2013; Jost and Herrmann, 1989).

We calculate the seismic moment tensor using least-squares inversion, and its location is determined by a grid search. Where available, the GCMT centroid location is employed as a reference. We use waveforms band-pass filtered between 12.5 and 20 s (0.05 - 0.08 Hz), and a total data length of 150 s (256 data points in each channel) for the inversion. At the initial stage, we create $0.1^\circ \times 0.1^\circ$ horizontal grid spacing, and 2 km interval depth. The time relative to the origin is limited from -1 s to 6 s to accommodate origin-time uncertainty and waveform alignment. Later on we adjust to a higher grid resolution of $0.05^\circ \times 0.05^\circ$.

2.2.2 Synthetic Test

To assess the stability and robustness of the inversion, we run synthetic tests using the Ak135 and PREM models. Synthetic waveforms based on an earthquake with M_w 6.5 that occurred on 2015-11-03 on Alor Island are generated for five elementary moment tensors. The GCMT centroid was used as a reference for the grid search, and the event is located in 124.9° E, and -8.2° S at 11 km depth. Arrival time is set to 0 second. The source generated using Ak135 Earth model (Kennett et al., 1995), and an inversion was done using both Ak135 and PREM.

The first test was designed to understand the effect of frequency bands used for the inversion (simulated test at 0.02 Hz to 0.10 Hz) on perfect Earth structures. The second test examined the impact of using an incorrect 1D Earth model in the inversion process, showing that the recovered source locations are misestimated by ~ 20 km horizontally and ~ 7 km vertically. Figure 2.3 shows the comparison of synthetic test results from for different elementary moment tensors at the lowest frequency of 0.02 Hz to 0.05 Hz. The complete results of different frequency bands

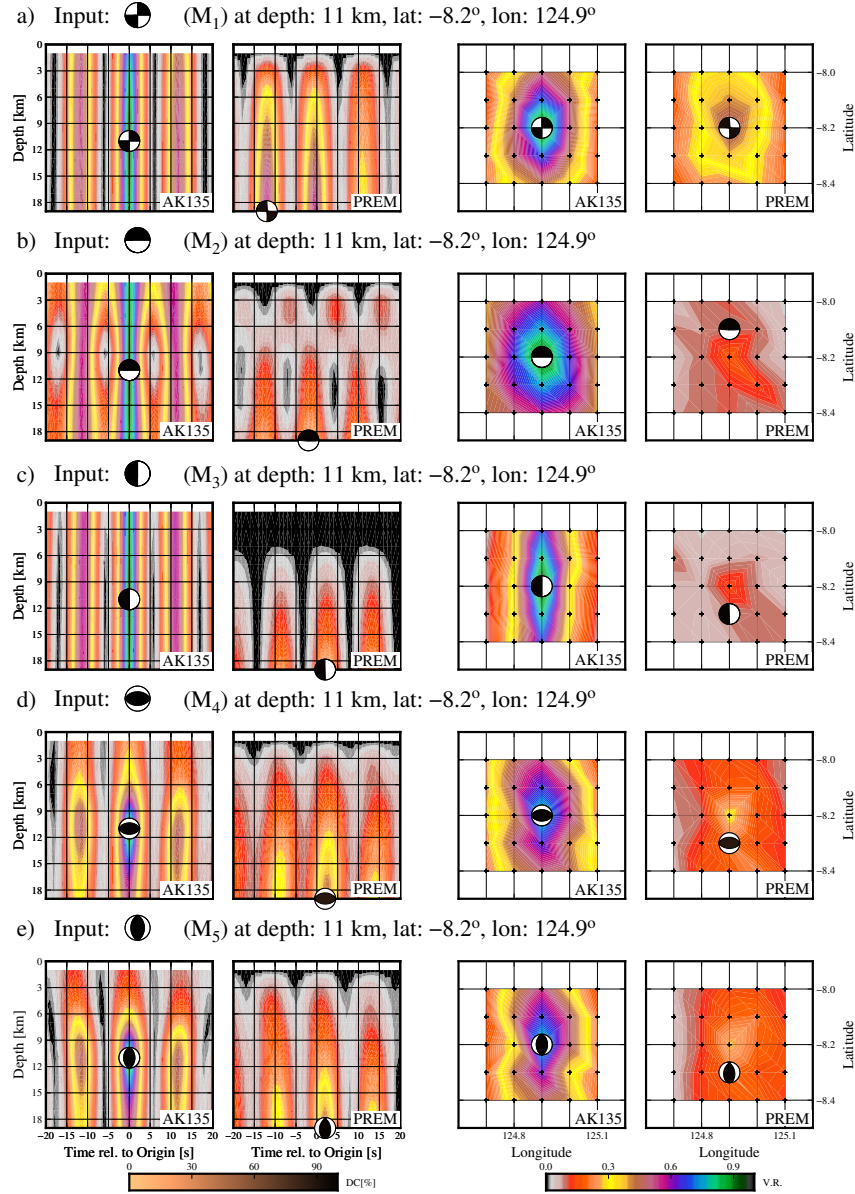


Figure 2.3: Comparison of synthetic tests for five basic elementary moment tensors (M_1 to M_5) using two different earth models: Ak135, and PREM. The synthetic source was generated using Ak135 and setup with arrival time at 0 s. Event located in Alor Island (Lon.: 124.9° , Lat.: -8.2°) at a depth of 11 km. The first and third column of figures shows the recovery of location, time and mechanism of the inputted source from inversion using the same model. Second and fourth column figures show unrecoverable of location, time and mechanism from inversion using PREM.

used are presented in Appendix [A](#).

The first and the third column of figures from the left show spatial and temporal results of the inversion using Ak135 from different source mechanism inputs (M_1 - M_5). The horizontal and vertical location (longitude, latitude, depth), time, and mechanisms are recovered from the inversion. High variance reduction values are shown at all depths for the first three mechanisms at lower frequency bands. This indicates insensitivity of the band used to the depth. It also suggests that the inversion has to be pushed to a higher frequency band for better results.

The second and the fourth column figures from the left show the effect of using the wrong Earth model. A very low percentage of recoveries (location and time) is obtained from using the wrong model. Low variance reduction values of less than 0.3 also confirmed this. Hence, the choice of 1D Earth model plays a very important role in the inversion for the moment tensor.

2.2.3 Developing 1D Models

Accurate source parameters of earthquakes—such as origin times, hypocentres, focal mechanisms, and magnitudes—depend on a well-developed 1D Earth model. Such a model also provides a reliable basis for calculating the Green's functions, which are essential for investigating earthquakes rupture processes ([Dreger and Helmberger, 1993](#)). Furthermore, the model may be used as an initial model to develop more complex 2D and 3D velocity models ([Kissling et al., 1994](#)).

Crustal structure complexity of Banda Arc-Continental collision zone requires specific regional and local 1D velocity model to be developed in order to obtain accurate earthquake source parameters. Raypaths from source to stations passing through crustal structures of different characteristics require a clearly defined model to be used for a specific raypath.

The computation of synthetic waveforms or P- and S-arrival travel times necessitates the use of an Earth model. In this study, we initially assessed a variety of Earth

models to replicate arrival times and generate complete waveforms for the largest foreshock (M_w 5.3) that occurred on 3 November 2015. Among the models tested were the Ak135 Earth model (Kennett et al., 1995), a series of 1D Earth models derived from integrated results of refraction/wide-angle reflection tomography, gravity modeling, and Multi-Channel reflection Seismic (MCS) imaging conducted in the region (Shulgin et al., 2009), and Earth models derived from a receiver function study (Syuhada et al., 2016). Additionally, we formulated two local 1D models based on a 3D shear wave velocity obtained from Ambient Noise Tomography (ANT) of the crust and uppermost mantle in the Banda Arc region (Zhang and Miller, 2021). The first 1D velocity model was constructed by interpolating velocities beneath the temporary station MTNG on Alor Island (see Figure A.3), while the second 1D model was derived by averaging the shear-wave velocities from five stations (MALK, ALRB, TL02, TL03, and TL04; see Figure 3.1) located near the mainshock epicenter (see Figure 2.1 and 3.1). A summary of these 1D velocity Earth models is presented in Figure A.3.

2.3 GPS-Based Block Modeling and Wavelet Analysis

2.3.1 Overview of GPS Measurements

Two types of GPS observables obtained from GPS satellites are the most important for positioning: pseudorange and carrier beat phase. Pseudorange provides the primary GPS observations for navigation. Although the observable is not precise enough to be used for high-precision geodetic surveys, it is useful for estimating the offsets of receiver clocks, resolving ambiguities, and repairing cycle slip in phase observations (Herring et al., 2015a; Blewitt, 1997; Leick et al., 2015).

A single phase-tracking channel recorded by a GPS receiver provides the carrier beat phases that are valuable in a high precision geodetic survey. The phases are always required for precise surveying (Leick et al., 2015). The observable is the

difference between the phase of the carrier wave received from the satellites and the phase of receiver oscillator. The phase can be measured accurately to a resolution of millimetres by eliminating the sources of errors and biases.

Unpredictable behaviour of the time and frequency standards serving as a reference for the transmitter and receiver is the dominant source of error in a phase measurement between a single satellite and receiver. The instability of these standards limits positioning to the several meter level of accuracy. Signal differencing is commonly employed to mitigate satellite and receiver clock errors, enabling high-precision positioning. To keep doubly differenced phase observation below 1 mm, pseudorange measurement, a priori knowledge of station coordinates, and satellite position have to be used to determine the offset of the station clock.

Between-station-difference or single-difference observable ([Herring et al., 2015a](#); [Van Sickle, 2015](#)) eliminates the effect of bias and instabilities in the satellite clock for a single satellite. This is done by differencing the phases of signals received simultaneously at two ground stations. Since the two receivers are both observing the same satellite at the same time, the difference between the satellite clock bias at the first and the second receiver is zero. Performing further phase differencing to eliminate receiver and satellite clock errors, and cycle ambiguity is common practice in pre-processing step of [GPS](#) data. Figure 2.4 illustrates the steps.

Another major source of error in single-frequency [GPS](#) measurement is ionospheric delays. The effect is quite significant for daytime observations made near solar maximum, exceeding several parts per million of the baseline length. Due to the dispersive nature of ionosphere, the delay effect can be reduced to a millimeter or less by performing an Ionosphere-free linear combination of L1 and L2 ([LC](#)) of dual-frequency observations. An [LC](#) is a weighted sum of carrier-phase or pseudorange measurements from different frequencies designed to suppress specific error sources or enhance desired signal components. By appropriately combining the two GPS carrier frequencies, [L1](#) and [L2](#), the first-order ionospheric delay can be largely

eliminated, leaving residual errors at the millimeter scale. This ionosphere-free linear combination **LC** is computed using the following formulation (Bock et al., 1986; Dong and Bock, 1989):

$$\phi_{LC} = 2.546 \phi_{L1} - 1.984 \phi_{L2} \quad (2.8)$$

This method is suitable for long baselines, but magnify the error due to highly cancellation for a short baseline less than a few kilometres. In this case, **L1** and **L2** are preferably treated separately as two independent observables.

Another useful combination of the two **L-bands** is called **LG**, which calculates the difference between **L2** and **L1** in the distance unit. In this equation, the **L2** phase is scaled by the "gear" ratio ($f_2/f_1=60/77=1227.6/1575.42$ for GPS; Herring et al. (2015a)):

$$\phi_{LG} = \phi_{L2} - 0.779 \phi_{L1} \quad (2.9)$$

In the **LG** phase, all geometrical and other non-dispersive delays are eliminated. Hence, a direct measurement of the ionospheric variation can be obtained.

With the availability of precise pseudoranges (**P-code**) for both frequencies, wide-lane (**WL**) combination—formed by differencing dual-frequency carrier-phase observations—can be constructed. This combination has a longer effective wavelength and is free of geometric and first-order ionospheric effects, making it particularly useful for resolving integer ambiguities. The widelane combination can be computed as the difference between the integer ambiguities on **L1** and **L2**, as follows:

$$WL = n_2 - n_1 = \phi_{L2} - \phi_{L1} + (P_1 + P_2)(f_1 - f_2)/(f_1 + f_2) \quad (2.10)$$

The combination above can be used to detect and fix cycle slips—sudden jumps in the measured carrier-phase caused by signal loss or interruptions—in one-way data. However, it should be combined with **LG** and **LC** to get the equal numbers

of cycles at [L1](#) and [L2](#) ([Herring et al., 2015a](#)). Phase ambiguities of [L1](#) and [L2](#) are determined by resolving the widelane ($n_2 - n_1$), and narrow lane (n_1) combination. With the help of unbiased and precise pseudorange data, the widelane combination can be resolved for baselines up to thousands of kilometres under any ionosphere conditions ([Herring et al., 2015a](#); [Blewitt, 1989](#)).

Orbit parameters computed by the [GPS](#) control centre are only accurate for navigational (1-5 part in 10^7 or 2-10 m), but not for crustal deformation studies. However, the International GNSS Service ([IGS](#)) provides accurate satellite motion information within 1 part in 10^9 (2 cm) from their computation based on the global network of more than 100 stations. Final products are available with a latency of 12–19 days, rapid products within 17-41 hours, and ultra-rapid products can be accessed within a few hours, though with slightly reduced accuracy.

Satellite motion modelling requires taking several parameters into account. Among those parameters, non-gravitational forces, are the most difficult to model. [Beutler et al. \(1994\)](#) and [Ziebart et al. \(2002\)](#) provide discussions of the precise orbital determination on [GPS](#) satellites. In principle, numerical integration of the equation of motion, instead of the analytical expression, is used for accuracy and convenience. [GAMIT](#) implemented equations introduced by [Ash \(1972\)](#) to compute [GPS](#) satellite trajectories.

Besides the satellite orbital parameters, several other factors have to be considered, such as offsets between the centre of mass and phase-centre of the antenna, the effects of geophysical phenomena on the ground station, and zenith delays caused by the neutral part of the Earth's atmosphere.

To estimate the relative positions of a set of stations, orbital and Earth-rotation parameters, zenith delays, and phase ambiguities by fitting to doubly differenced phase observations, [GAMIT](#) includes a weighted least squares algorithm. Since the functional model relating the observations and parameters is non-linear, [GAMIT](#) produces two solutions, the first to obtain coordinates within a few decimetres, and the

second to obtain the final estimates (Herring et al., 2015a). However, the outputted estimates and quasi-observations of station positions, orbital and Earth-rotation parameters of GAMIT are used in practice, which are then inputted to GLOBK for the estimation of positions and velocities (Dong et al., 1998).

2.3.2 GPS Data Processing and Analysis

GPS observations were pre-processed using Translation, Editing, and Quality Check (TEQC) (Estey and Meertens, 1999) to perform data quality checks and convert proprietary receiver files into the Receiver INdependent EXchange (RINEX) format prior to geodetic processing. The RINEX observations were subsequently processed using the GAMIT/GLOBK software package (version 10.70; Herring et al., 2015a,b), a widely adopted geodetic processing system for high-precision GNSS analysis and terrestrial reference frame realization. The data were processed following the standard two-step workflow implemented in GAMIT/GLOBK, in which daily loosely constrained network solutions are first generated using GAMIT and subsequently combined in GLOBK through sequential Kalman filtering to estimate consistent station coordinates and velocities within the adopted International Terrestrial Reference Frame (ITRF). This processing strategy has been extensively applied in geodetic and tectonic studies for more than three decades and is well established for terrestrial reference frame realization and crustal deformation analysis (e.g., Bock et al., 1986; Tregoning and McQueen, 2001; Reilinger et al., 2006; McClusky et al., 2003; Koulali et al., 2015, 2016, 2017; Li, 2021; Mlawala and Saria, 2023). The overall processing workflow consists of data preprocessing, daily network processing, reference frame realization, coordinate time-series analysis, and velocity estimation, which are described in the following subsections.

2.3.2.1 GPS Data Processing Using GAMIT

Daily GPS observations were processed using GAMIT to estimate loosely constrained daily network solutions from dual-frequency carrier-phase and pseudorange observations. GAMIT employs a double-difference least-squares processing strategy, which substantially reduces satellite and receiver clock errors while improving ambiguity resolution and the precision of relative station positioning. During each daily adjustment, station coordinates, atmospheric zenith delays, satellite orbit parameters, and Earth orientation parameters (EOPs) are estimated simultaneously from the GPS observations (Herring et al., 2015a,b).

Processing was performed using the ionosphere-free linear combination of the GPS signal at 1575.42 MHz (L1) and GPS signal at 1227.60 MHz (L2) carrier-phase observations together with the IGS Final precise satellite orbit and clock products, EOPs, and antenna phase-center calibrations provided by the International GNSS Service (IGS). Tropospheric propagation delays were estimated as stochastic zenith wet delay parameters, while the hydrostatic component was modeled using the Global Pressure and Temperature-2 (GPT2) empirical tropospheric model and mapped to the line of sight with the Global Mapping Function (GMF). Solid Earth tides, ocean tide loading, pole tides, and relativistic effects were modeled following the conventions of the International Earth Rotation and Reference Systems Service (IERS) (Lagler et al., 2013; Herring et al., 2015a,b).

The daily solutions were generated as loosely constrained network solutions and stored as binary GAMIT h-files, which contain the estimated parameters and their complete variance-covariance matrices. Preserving the full covariance information allows statistically rigorous combination of the daily solutions in GLOBK for reference frame realization and estimation of consistent station coordinates and velocities.

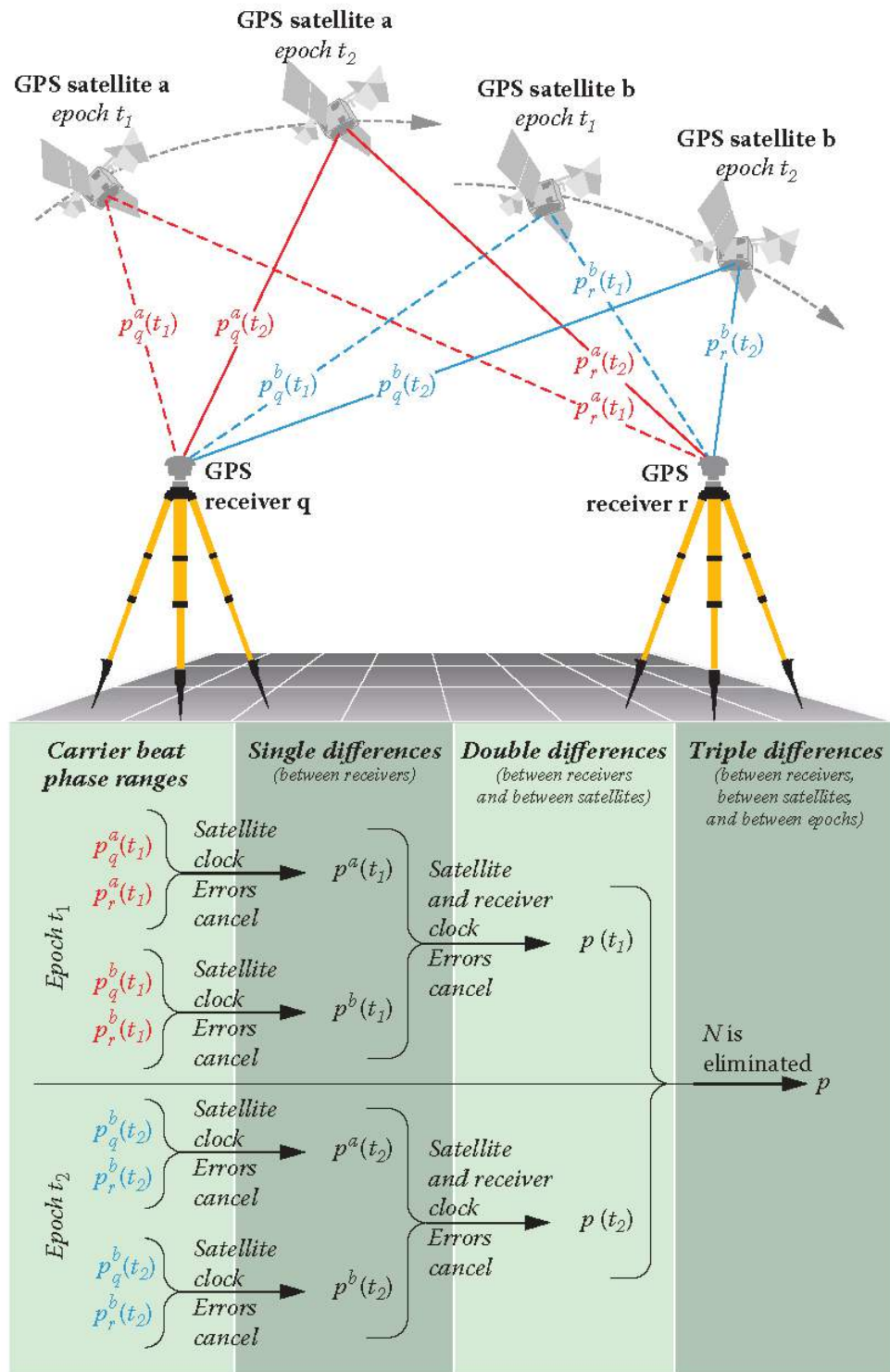


Figure 2.4: Differencing methods to eliminate the source of errors in GPS observables: single, double and triple differences. (Van Sickle, 2015)

2.3.2.2 Network Combination and Reference Frame Realization Using **GLOBK**

The loosely constrained daily solutions produced by **GAMIT** were combined using the **GLOBK** software package, which employs a sequential Kalman filter to estimate a consistent set of station coordinates and velocities while rigorously propagating the full covariance information from each daily solution. Rather than reprocessing the original **GPS** observations, **GLOBK** treats the daily h-files as quasi-observations and recursively updates the network solution as additional daily estimates are incorporated.

To realize the terrestrial reference frame, each daily regional solution was combined with corresponding global h-files produced by the **MIT** and/or the **SOPAC**. Between 10 and 15 continuously operating **IGS** reference stations were included in each daily solution to provide orbital control and stabilize the regional network within the adopted **ITRF2014**. Reference frame realization was performed in **GLORG** (a **GLOBK** module) using generalized constraints applied to the selected reference stations through a six-parameter Helmert transformation consisting of three translations and three rotations. This approach minimizes distortion of the regional network while maintaining consistency with the global reference frame.

Following reference frame realization, **GLOBK** was used to generate station coordinate time series and estimate velocities from the combined daily solutions through weighted least-squares adjustment. Because **GLOBK** assumes that the input daily solutions are free from significant unmodeled discontinuities and cannot independently resolve phase ambiguities or correct deficiencies in the original observations, potential non-tectonic offsets must be identified and corrected prior to deriving reliable velocity estimates. These discontinuities may arise from equipment changes, earthquakes, monument instabilities, or processing artifacts, and if uncorrected, can introduce biases into the estimated station velocities.

To systematically identify stations potentially affected by coseismic deformation, we evaluated all earthquakes occurring within the observation period and estimated

their potential influence radius using the empirical relationship proposed by [Herring et al. \(2016\)](#). Stations located within the calculated influence radius of each earthquake were subsequently examined for possible discontinuities in their coordinate time series.

$$d = 2.5 \times 10^{-3} \times 5^M \quad (2.11)$$

where d represents the estimated earthquake influence radius and M is the earthquake magnitude reported by the [USGS](#) National Earthquake Information Center ([NEIC](#)).

Coordinate time series of stations located within these influence zones were inspected for coseismic offsets. For example, the Kalabahi station (CKAL) recorded a clear coseismic displacement associated with the M_w 6.2 earthquake that occurred on Alor Island on 3 November 2015 (Figure [C.3](#)).

Jumps in the [GPS](#) position time series were identified and corrected using the `tsview` module of the [GLOBK](#) package. The time series were visually inspected to detect discontinuities associated with equipment changes, earthquakes, or processing artifacts. These offsets were modeled as step functions at the corresponding epochs, allowing pre- and post-event segments to be aligned while preserving the long-term trend. The MATLAB tools `tsview` / `velview` were used to visualize the time series, identify offsets, and generate the figures. This procedure reduces bias in station velocity estimates caused by non-tectonic discontinuities.

2.3.3 Deformation Models

Two main categories of models have been proposed to describe crustal deformation: continuum models and block models ([Thatcher, 2007](#)).

The continuum model represents continental deformation as a spatially continuous velocity or strain field, commonly parameterized using interpolation techniques, wavelet-based methods, or continuum mechanics formulations (e.g., [England and](#)

McKenzie, 1982; England and Molnar, 1997; Thatcher, 2007). These approaches assume that deformation is distributed rather than localized onto discrete rigid blocks, and they are often used to estimate strain-rate fields (e.g., Holt et al., 2000; Haines and Holt, 1993), characterize regional deformation patterns, and investigate lithospheric rheology and viscous flow behavior (e.g., Flesch et al., 2000, 2001; England and Molnar, 2005). Although brittle faulting accommodates deformation in the upper crust, its cumulative effect is treated implicitly within the continuous deformation field.

In contrast, the block model assumes that actively deforming regions consist of discrete rigid or quasi-rigid blocks separated by active faults. Deformation is primarily localized along block-bounding faults, while internal block deformation is typically small or parameterized (Murray and Segall, 2001; McCaffrey et al., 2002; McCaffrey, 2005; Meade and Hager, 2005; Thatcher, 2007). Block models explicitly estimate block rotations and fault slip rates, providing a kinematic description of crustal deformation.

Both the continuum model and the block model serve as frameworks to understand the relationship between observed surface deformation and the underlying deformation mechanisms. Each model provides a distinct perspective on crustal deformation, offering insights into different aspects of the Earth's lithosphere dynamics and deformation processes.

In this study, we utilized block modeling approach by McCaffrey et al. (2002); McCaffrey (2005), McCaffrey et al. (2007) and Meade and Hager (2005) to describe present-day deformation observed in the GPS data, where deformation is largely accommodated by relative motion between quasi-rigid blocks bounded by active faults.

2.3.4 Kinematic Block Modeling

Elastic block modeling provides a kinematic framework for interpreting geodetic velocity fields in terms of rigid block motions and elastic deformation associated with fault locking. In this approach, the crust is divided into discrete blocks separated

by predefined fault geometries. Each block undergoes rigid rotation relative to a reference frame, while elastic strain accumulates on partially locked faults at block boundaries. The model simultaneously inverts for block rotation poles, fault coupling (locking) coefficients, and, where permitted, internal block strain, allowing both long-term rigid motion and interseismic elastic deformation to be estimated consistently from GPS observations (McCaffrey et al., 2002; McCaffrey, 2005; McCaffrey et al., 2007; Meade and Hager, 2005).

Interseismic surface velocities reflect the combined effects of relative block motion, elastic strain accumulation due to fault locking, and minor internal deformation within blocks. Faults are represented as discretized planar surfaces embedded in a homogeneous, isotropic elastic half-space, using elastic dislocation solutions (Okada, 1985, 1992). Fault coupling describes the fraction of long-term slip that is locked during the interseismic period and contributes to elastic strain accumulation in the surrounding crust (Savage, 1983; McCaffrey et al., 2002; Meade and Hager, 2005). Spatial variations in coupling are commonly interpreted as reflecting heterogeneous locking behavior, including strongly locked asperities and creeping segments. Low coupling indicates predominantly aseismic slip, whereas high coupling indicates stress accumulation that may be released in future earthquakes.

The method requires predefined fault geometries and closed block polygons. In regions where fault connectivity is incomplete or poorly constrained, artificial block closure may be required, which represents a limitation of the approach. Nevertheless, elastic block models have been widely applied to quantify fault slip rates, block rotations, and interseismic strain accumulation in tectonically active regions (Wallace et al., 2004; McCaffrey, 2005; McCaffrey et al., 2007; McCaffrey, 2009; Reilinger et al., 2006; Meade and Hager, 2005; Socquet et al., 2006; Loveless and Meade, 2011; Hammond et al., 2011; Koulali et al., 2015, 2016, 2017; Elliott and Freymueller, 2020; Özbey et al., 2021; Zhao et al., 2023, and many others).

In the block model, the long-term rigid block velocity (V_R) is determined by the

rotational plate motion, represented by an angular velocity vector. On the shallow locked portion of the crust, the elastic contribution (V_E) in the velocity field is provided by an elastic dislocation with a slip rate equal in magnitude but opposite in direction (i.e., back-slip; [Savage, 1983](#)) to the relative movement of blocks projected onto the fault plane. This elastic back-slip contribution is driven by the relative block rotations, maintaining kinematic consistency between block motion and long-term fault slip rates.

Additionally, the model allows for the consideration of internal strain of blocks (V_S) as an additional source of deformation, since minor faults are not explicitly included in the block geometry ([McCaffrey, 2005](#)). The interseismic velocity field (V_I) is therefore modeled as the sum of these three components:

$$\mathbf{V}_I = \mathbf{V}_R + \mathbf{V}_E + \mathbf{V}_S \quad (2.12)$$

where V_R , V_E , and V_S are the velocity contributions from rigid block rotation, elastic strain, and internal block deformation, respectively, producing the observed GPS interseismic velocities.

The individual velocity components are formulated as follows:

$$\mathbf{V}_R(\mathbf{r}) = \boldsymbol{\omega} \times (\mathbf{r} - \mathbf{r}_c), \quad (2.13)$$

$$\mathbf{V}_E(\mathbf{r}) = \sum_k \mathbf{G}_k(\mathbf{r}) \dot{\mathbf{s}}_k, \quad (2.14)$$

$$\mathbf{V}_S(\mathbf{r}) = \boldsymbol{\varepsilon} \cdot (\mathbf{r} - \mathbf{r}_0), \quad (2.15)$$

Here, $\boldsymbol{\omega}$ is the block rotation vector, $\mathbf{r}$ the station position, $\boldsymbol{\varepsilon}$ the block strain rate tensor, and $\mathbf{G}_k \dot{\mathbf{s}}_k$ the elastic back-slip contribution from fault k . In this study, block rotations, elastic strain accumulation on faults, and internal block strain are modeled using the TDEFNODE software ([McCaffrey et al., 2002, 2007](#)).

A block, as defined in [McCaffrey et al. \(2002\)](#) and [McCaffrey et al. \(2007\)](#), is a

closed polygon that undergoes rotation and elastic deformation along its boundaries due to friction with adjacent blocks, as well as uniform strain deformation. The computation algorithm described in the two studies calculate one angular velocity and one uniform horizontal strain rate tensor for each block, in addition to determining the locking distributions for fault planes that define block boundaries. Consequently, the resulting velocity at any point ($V_k(\mathbf{X})$) is computed according to the following equation:

$$V_k(\mathbf{X}) = [{}_R\boldsymbol{\Omega}_B \mathbf{x} \mathbf{X}]_k + \varepsilon_{kk} \Delta \mathbf{X}_k + \varepsilon_{kl} \Delta \mathbf{X}_{kl} + \varepsilon_{ll} \Delta \mathbf{X}_l + \sum_{j=1,2} \sum_{i=1,N} [V_j \phi_i] G_{jk}(\mathbf{X}, \mathbf{Q}_i) \quad (2.16)$$

where $\mathbf{X}$ represents the position of the surface observation point, k denotes the Cartesian components of the velocity vector, and $\Delta \mathbf{X}$ signifies the offset from the center of the polygon used to compute the uniform internal strain rate. N denotes the total number of nodes. The variables ϕ_i , $(\varepsilon_{kk}, \varepsilon_{kl}, \varepsilon_{ll})$, and $G_{jk}(\mathbf{X}, \mathbf{Q}_i)$ represent the locking fraction at node i , internal strain rate tensor components, and unit response functions, respectively (Özbey et al., 2021).

The goodness of fit of the parameter set is determined by minimizing the χ^2 value:

$$\chi_n^2 = \left[\sum_{i=1,N} r_i^2 / (\sigma_i F)^2 \right] / (n - k) \quad (2.17)$$

where r_i is residual (observed minus calculated velocity), σ_i is standard deviation of the observation, F is scaling factor, n is the number of observations, and k is number of free parameters.

To optimize the parameters and minimize the χ^2 value, a combination of simulated annealing and downhill simplex minimization techniques, as described by Press et al. (1989), is applied. Once the minimum χ^2 is achieved, the parameter co-

variance matrix is estimated using singular value decomposition of the linearized normal equations ([McCaffrey et al., 2002](#)).

2.3.5 Spherical Wavelet Method

The spherical wavelet method is a powerful tool for deriving continuous velocity fields from discrete velocity measurements obtained from [GPS](#) data. This approach enables the calculation of a continuous horizontal strain-rate field, which is crucial for understanding the deformation patterns across regions like the Banda Arc. By utilizing a wavelet-based multiscale approach, the method effectively addresses the challenge of irregularly spaced geodetic stations, allowing for a more accurate representation of surface velocities on a sphere.

The core of this method, as described by [Tape et al. \(2009\)](#), lies in its ability to represent surface velocities as a superposition of values obtained at different spatial scales. This means that the velocity at any given point on Earth's surface is influenced by surrounding data across various levels of detail, capturing both large-scale trends and finer, localized variations. The multiscale nature of spherical wavelets is key to this process, as it enables the method to adapt to the varying density of [GPS](#) stations in different regions.

A significant advantage of this approach is its ability to selectively apply wavelets from progressively finer meshes only where the data density justifies it. In areas with dense [GPS](#) station coverage, short-scale spherical wavelets are used to capture detailed local variations. Conversely, in regions with sparse station coverage, the method relies on long-scale wavelets to estimate broader trends. This adaptive scaling ensures that the smallest resolved processes are matched to the local density of observations, improving the overall accuracy of the velocity field estimation.

Rupture pattern of 2015 Alor earthquake sequence, Indonesia

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H. Nugroho,¹ B. Hejrani^{1,2}, S. Mousavi¹, and M. Miller¹

Foreword

In this chapter, we investigate the 2015 earthquake sequence on Alor Island, Indonesia, with the aim of understanding how a moderate-to-large crustal event expresses deformation within the Timor microplate and the broader Banda Arc transition zone. Rather than being considered solely as an isolated seismic event, the Alor sequence is of particular interest because of its location within a key tectonic transition where multiple independent geophysical observations converge, making it a natural probe of ongoing plate boundary reorganisation and internal microplate deformation.

The sequence occurred at the leading edge of the largely accreted Banda forearc, in the immediate hanging wall of the Wetar Thrust ([Silver et al., 1983](#)), a major structure accommodating convergence between Australia and the Banda Arc. It is also situated at a pronounced discontinuity in [GPS](#)-derived velocity fields across eastern Indonesia (e.g., [Bock et al., 2003](#); [Genrich et al., 1996](#); [Nugroho et al., 2009](#)), close to evidence for arc-parallel extensional kinematics in the Wetar Strait ([Masson et al., 1991](#)). In addition, seismic velocity models indicate a marked upper-crustal shear-wave velocity (V_s) discontinuity in this region ([Miller et al., 2021](#); [Zhang and Miller, 2021](#)),

¹Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia.

²Geoscience Australia, Symonston, ACT, 2609, Australia.

suggesting strong lateral contrasts in crustal structure. Collectively, these observations indicate that the Alor region represents a mechanical and kinematic boundary within the Timor–Banda system.

These characteristics make the Alor earthquake sequence particularly valuable for addressing two key research questions of this thesis. First, it provides constraints on the present-day state of plate boundary reorganisation across Indonesia, Australia, and New Guinea at a regional scale. Second, it offers a unique opportunity to investigate the internal deformation of the Timor Block as defined by (Bird, 2003), particularly in terms of how strain is partitioned within the semi-accreted arc and collision zone. A moderate-to-large earthquake occurring in such a structurally and kinematically complex setting therefore has the potential to illuminate both boundary-scale plate interactions and intra-block deformation processes.

To address these questions, we apply CMT inversion using seismic waveform data recorded by a temporary broadband seismic deployment spanning the Banda Arc region. To improve waveform fitting and source parameter resolution, we develop a set of regionally optimised one-dimensional Earth models tailored to the study area. These models are used to perform CMT inversions by matching synthetic waveforms, computed through forward modelling in the assumed Earth structure, to observed seismograms across multiple stations. The inversion yields estimates of the seismic moment tensor, from which we derive key source parameters including fault geometry (strike, dip, and rake), centroid depth, and moment magnitude.

In addition, we relocate earthquake hypocentres using a probabilistic approach, which allows improved constraints on the spatial relationship between foreshocks, the mainshock, and aftershocks. This analysis provides a refined estimate of the fault plane geometry for the largest foreshock and the mainshock. Finally, we analyse the rupture evolution of the sequence, which exhibits a predominantly westward propagation pattern. These results reveal the activation of a previously unrecognised fault structure on Alor Island, which we interpret as a significant new block bound-

ary within the regional kinematic framework, a topic which will be addressed in Chapters 4 and 5.

3.1 Abstract

A sequence of earthquakes occurred on Alor Island, Nusa Tenggara Timur, Indonesia, beginning in November 2015 with the mainshock (M_w 6.2) on 4 November 2015. We calculate the Centroid Moment Tensor (CMT) solutions for nine of the earthquakes with $M_w \geq 3.9$, which occurred between November 2015 and March 2016 using records from a temporary array of 30 broadband instruments in eastern Indonesia and Timor-Leste (YS network). Our CMT results reveal an interesting pattern of ruptures in this order: a) three foreshocks of M_w 4-5.3 all with strike-slip mechanisms that occurred with a centroid depth of ~ 13 km in the three days prior to the mainshock b) the mainshock on 4 November 2015, with M_w 6.2 that occurred with a deeper centroid (~ 25 km) and a strike slip mechanism similar to the foreshocks, c) followed by five aftershocks with $M_w > 3.9$ at depth ~ 3 -15 km. We further determine the fault plane and rupture direction of the main shock and the largest foreshock (M_w 5.3) by relocating the hypocenter and examining its geometrical location with respect to the centroid. We find that the fault plane strikes $97^\circ \pm 9^\circ$ from north and that the fault ruptures westward. We propose that the rupture of this sequence of events initiated at depth ~ 10 km, propagating westward and triggering the main shock to rupture at a deeper depth (within lower crust) on a similar faulting system. The aftershocks migrate back to shallower depths and mainly occur at depth < 10 km.

3.2 Introduction

The Banda Arc region of eastern Indonesia has a complex tectonic setting that involves four converging and colliding major plates, the Australian Plate, the Pacific

Plates, the Philippine Sea Plate, and the Sunda Plate, that has been ongoing since the Late Oligocene (Hall, 2002, 2012; Hamilton, 1979; Hinschberger et al., 2005). In the western portion of the Banda arc, the oceanic component of the Australian plate has subducted beneath the Sunda Plate that spans over 5,000 km from Sumatra to the Lesser Sunda Islands (DeMets et al., 1994; Hall, 2002; Bock et al., 2003; Müller et al., 2008). From Sumba to the east, the tectonic regime changes from subduction of oceanic lithosphere along the Sunda margin to a collision of the continent-island arc along the Banda arc (Hall, 2002; Audley-Charles, 1975, 2004; Milsom, 2001; Shulgin et al., 2009; Harris, 2011) known as Sunda-Banda arc transition zone, and the inner arc comprises volcanic islands (Spakman and Hall, 2010). Studies of seismic activity (McCaffrey and Nábělek, 1984) and marine seismic surveys (Silver et al., 1983; Breen et al., 1989; Masson et al., 1991) have identified the back-arc further north, from the north of Flores to the north of Wetar. Most seismic activity is concentrated in the Banda arc transitional zone.

Figure 3.1 presents a compilation of $M_w > 6.5$ earthquakes for both historical (1000-1903) and instrumental-era (1905-2022). Within the historical time frame, five strong-great earthquakes were recorded (Albini et al., 2014; Griffin et al., 2019; Musson, 2012, red stars in Figure 3.1). Recently, Martin et al. (2022) reported an additional eleven events, including five great earthquakes (M 8.0) that occurred during the same time frame. However, their study does not provide source locations for these events.

The earthquakes from 1905 to 2022 acquired from the NEIC catalog (Masse and Needham, 1989) includes 25 shallow events with M_w 6.6-7.5 (circles colored by depth in Figure 3.1). Both historical and instrumental-era earthquake compilations indicate the majority of seismicity occurred within the region between 7° S and 9.5° S. Few significant and damaging historical earthquakes have been documented near Alor (Griffin et al., 2019; Harris and Major, 2017; Coudurier-Curveur et al., 2021; Das, 2004).

To understand the ongoing tectonic evolution of the region, 30 broadband seis-

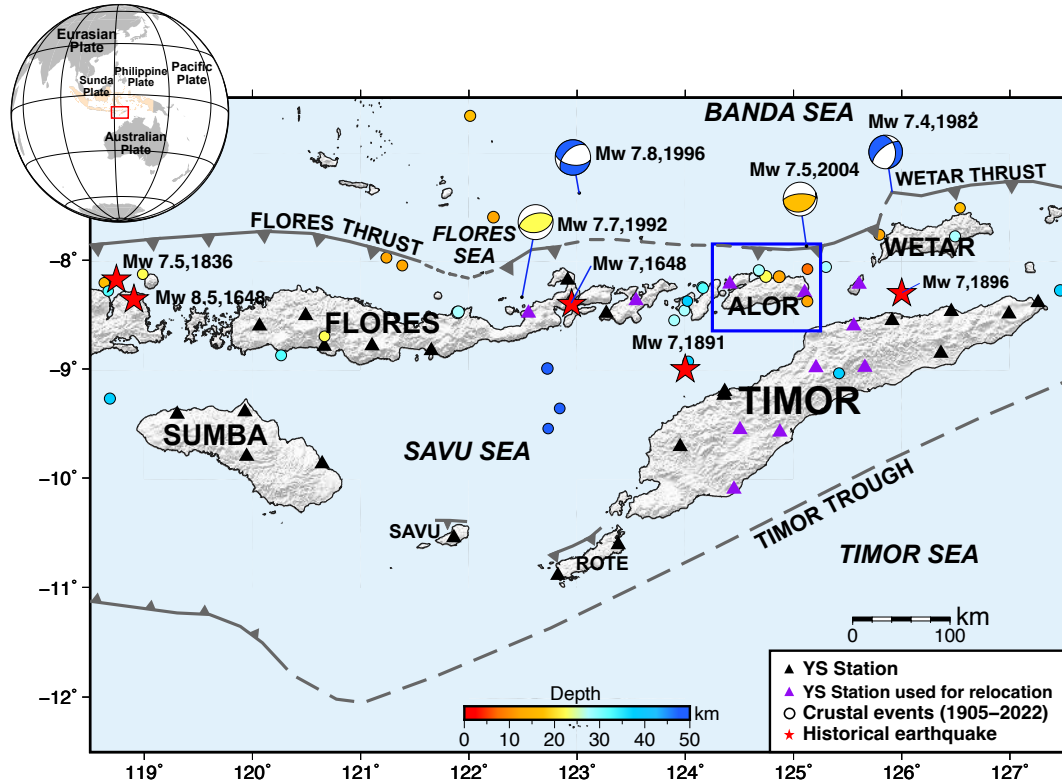


Figure 3.1: Crustal events (1905-2022) of $M_w > 6.5$ acquired from United States Geological Survey/National Earthquake Information Center catalog, and historical events (1000-1903) from [Albini et al. \(2014\)](#), [Griffin et al. \(2019\)](#), and [Musson \(2012\)](#). Focal mechanisms for the four modern events are from [GCMT \(globalcmt.org\)](#). The blue rectangle shows the focus study area of Alor Island which is shown in Figure 3.5.

monometers were deployed around the Banda Arc-continental collisional zone from March 2014 to January 2019 ([Miller, 2019](#); [Miller et al., 2016](#), YS network, Figure 3.1). Using the data recorded this temporary network, [Jiang et al. \(2022\)](#) relocated events in the region using arrival data picked by a machine-learning-based algorithm to construct an earthquake catalog. In this study, our focus is on investigating the most significant event in their catalog: the M_w 6.2 earthquake that occurred on Alor Island on 4 November 2015. Notably, this event was one of the largest crustal earthquakes in the region in recent history and was recorded by the 2014-2019 temporary deployment (Figure 3.1). The main event was preceded by three foreshocks and followed by over 1420 aftershocks of $M \leq 5.3$ ([Jiang et al., 2022](#)). This sequence of events damaged approximately 1,500 buildings without any reported injuries ([Setiyono et al.,](#)

2019; [Funning and Garcia, 2019](#)). The [GCMT](#) catalog reported the main shock and two foreshocks with $M_w > 4.9$ with the main shock having a centroid depth of about 12 km and the two foreshocks with an approximate depth of 14-16 km. The [GCMT](#) mechanisms for these events are strike slip with a strong normal component, indicating a combination of significant lateral movement along the fault and a vertical component of ground displacement.

The Alor earthquake sequence recorded by the temporary network provides a fantastic opportunity to study the rupture characteristics and better understand how it fits in the complex tectonic of the region. Using local to regional data and 1D region-specific models, we can estimate the fault plane and rupture direction for events with $M_w > 5.5$ and push waveform modeling towards higher frequencies to obtain Centroid Moment Tensor ([CMT](#)) for earthquakes with $M_w < 5.0$ ([GCMT](#) catalog uses global low-frequency data for events with $M_w > 5.0$).

In this study, we perform centroid moment tensor inversions for events with $M_w \geq 3.9$ in the 2015 Alor earthquake sequence using three component broadband data recorded by the YS network. We constructed a local 1D Earth velocity model using arrival times picked manually from waveforms of the local seismicity to compute synthetic waveforms for a set of grid of points across Alor Island and its proximity. We also identify the fault plane of the largest foreshock and the main shock by relocating its hypocenter in a probabilistic framework.

The 2015 earthquake sequence in Alor Island is significant in confirming the presence of an active fault in the region. Results in this study improves our understanding of the faulting system compared to the interpretation based solely on the Side Looking Airborne Radar ([SLAR](#)) data through surface impression ([Silver et al., 1983](#)).

3.3 Earthquake Data Preparation

Between 23 October 2015, and 4 November 2015, a total of 57 small earthquakes with $M < 4$ were recorded on Alor Island prior to the mainshock. The number of events

rapidly increased from 18 on 1 November to 28 on 3 November. Among those, three foreshocks occurred on 1 November and three with M_w 4.0, 4.6, and 5.3. Then the main event occurred on 4 November 2015, with M_w 6.2, followed by numerous aftershocks (Jiang et al., 2022).

We used three component broadband data recorded by the YS network for waveform modeling and picking P- and S- arrivals. For waveform modeling, we cut windows of 150 s from the origin time, removed the mean and trend, corrected for instrument response and downsampled to 4 Hz. We filtered the data at the frequency band 0.05-0.08 Hz to perform waveform modeling for CMT solutions. We applied the same sampling and filter to the synthetic data. At this stage, we also visually inspected the seismograms for any clipped waveforms or noisy data. We picked P-wave arrivals on vertical components filtered around 1 Hz (0.5-2 Hz) and S-wave arrivals on the transverse components filtered at 0.1-0.5 Hz (Figures A.1 and A.2, available in the supplemental material to this article).

3.4 Methods

To analyze the source characteristics of the Alor earthquake sequence we calculated the Centroid Moment Tensor (CMT) solution through 4D grid search in the vicinity of the initial location and time following Kikuchi and Kanamori (1991) and Hejrani et al. (2017). For the two largest events, we also estimated the hypocenter and used it to distinguish the fault plane from the auxiliary plane following Zahradnik et al. (2008).

3.4.1 CMT solution

Using waveform modeling, the CMT solution represents a moment tensor (MT) estimation for a "centroid" point source approximation (C) of the dominant slip region(s) along the fault (Dziewoński et al., 1981). We estimate the MT components via least squares and the centroid via grid search. In this approach, the elementary seismo-

grams for six basic mechanisms are generated (through a given Earth model) for a set of trial points in the 3D vicinity of the hypocenter. At each point source, the MT components are resolved via the least squares method following the [Kikuchi and Kanamori \(1991\)](#) convention and the fit to the data are measured as follows ([Hejrani et al., 2017](#)):

$$Fit = 1 - \sqrt{\frac{\sum_{i=1}^n (U(i) - S(i))^2}{\sum_{i=1}^n (U(i))^2}} \quad (3.1)$$

in which U is the observed, and S is the synthetic data. The centroid location and time are resolved through a 4D spatiotemporal grid search over the trial points. The optimum centroid location and time are defined as the points with the maximum fit to the data (Eq. 3.1). Following [Hejrani and Tkalčić \(2020\)](#), we assess the resolvability and the stability of the [CMT](#), by considering a set of solutions given a threshold below the maximum fit. This results in a family of solutions rather than a single [CMT](#) solution for each event, which is then used to assess the stability of the nodal planes. We considered a range of 1D Earth models to simulate the elementary seismograms on all the stations in the YS network, which we discuss in [3.4.4](#) and [3.5](#).

3.4.2 Hypocenter solution

The hypocenter is an estimation of the rupture initiation location and time. We used the NonLinLoc software package ([Lomax et al., 2000, 2009](#)) to invert P- and S-arrival times for hypocenter in a probabilistic framework, which relies on the use of normalized and unnormalized Probability Density Function (PDF)s. We used the Oct-Tree algorithm implemented in NonLinLoc to effectively search the model space to relocate the earthquakes in a nonlinear probabilistic framework.

To relocate the events, we hand-picked P- and S-arrivals on all stations of the YS network with epicentral distance less than 275 km (Figure [A.1](#) and [A.2](#)). Similar to the [CMT](#) solution, we repeated the inversion in a range of 1D local Earth models (Figure [A.3](#)) to assess the stability of the results. In this study, we have only relocated

the largest foreshock and the mainshock by manual picking the P and S arrivals using stations identified in the purple symbols in Figure 3.1 with the aim of identifying the fault plane for these two particular earthquakes. Jiang et al. (2022) automatically picked arrivals employing a Machine Learning technique based on Mousavi et al. (2020) for earthquakes that occurred during the entire duration the temporary broadband deployment (YS network; Miller, 2019; Miller et al., 2016, Figure 3.1). The focus of their study was to create a catalog for the entire region, which located $\sim 20,000$ events in the wider eastern Indonesia region. Nevertheless, our main objective center around conducting a thorough analysis of the largest foreshock and mainshock of the Alor earthquake sequence. As a result, we have opted for the use of manually picked data and local 1D models developed specifically for the events in the Alor region, which are essential in reducing the horizontal and vertical error in hypocenter location and hence improving the reliability of fault-plane identification as is discussed further in section 3.4.3 and 3.5.2.

3.4.3 Fault-plane estimation and its resolvability

The focal mechanism representation of a pure double-couple seismic source consists of two nodal planes, called the fault plane and the auxiliary plane. Distinguishing one from the other requires additional data and analysis such as, aftershock distributions (e.g., Yang et al., 2022; Zhou et al., 2021, 2022) and, in case of shallow earthquakes, detailed surface rupture imaging and satellite imagery (e.g., King et al., 2018, 2019; Yang et al., 2021; Attanayake et al., 2020; King et al., 2021; Sellmann et al., 2022, 2023; Han et al., 2022; Mohammadi, 2022). We follow the approach by Zahradnik et al. (2008) to distinguish the fault plane from the auxiliary plane. This geometrical technique suggests that the nodal plane that encompasses both hypocenter (H) and centroid (C) is more likely to be the fault plane. The method relies on a simplified fault-plane model, wherein the rupture is initiated at the H on the fault plane and unilaterally continues towards the dominant slip region (C) on the fault. Therefore,

grated results of a refraction/wide-angle reflection tomography, gravity modelling, and MCS imaging conducted in the region (Shulgin et al., 2009). We also tested Earth models derived from a receiver function study (Syuhada et al., 2016). In addition, we derived two local 1D models from a 3D shear wave velocity derived from ANT of the crust and uppermost mantle in the Banda Arc region (Zhang and Miller, 2021). The first 1D velocity model was obtained by interpolating velocities under the temporary station MTNG on Alor Island (Fig. A.3), and the second 1D model was derived by averaging the shear-wave velocities from five stations (MALK, ALRB, TL02, TL03, and TL04; Fig. 3.1) closest to the mainshock (Fig. 3.1). A summary of these 1D velocity Earth models are shown in Fig. A.3.

We examined the fit between the synthetics computed from these velocity models and the waveforms recorded by the YS network for the CMT solutions. None of these models generated synthetics that fit the waveforms which is expected given the structural complexity of the crust in this region (Zhang and Miller, 2021). The significant variations in crustal structure strongly affect the surface waves, which are dominant in regional full waveform CMT inversion at frequencies < 0.1 Hz. This effect may not be as significant for body wave travel time data (Mousavi et al., 2023). Therefore, a model that works well for waveform simulation (dominated by surface waves) may not perform as well for body wave arrival prediction and vice versa.

Following these tests, we developed a 1D Earth model specific to the Alor region using arrival-time data of local earthquakes in Alor and adjacent areas recorded by the YS network (Figure A.3). We used the VELEST software (Kissling et al., 1994, 1995) to simultaneously relocate the events and estimate a 1D Earth model. To avoid any bias towards a particular initial model, we ran the inversion over 1,000 random input models and selected the one with minimum Root Mean Squared (RMS) (e.g., Walsh et al., 2009; Mousavi et al., 2015, 2017; Kamer et al., 2017). The synthetics simulated from our 1D model achieved correlation of $> 60\%$ on all waveforms used in our waveform inversion, making it our preferred model for CMT inversion (see

the Result section and Fig. 3.2a). All the 1D models tested, including the preferred model, are shown in Figure A.3.

3.5 Results

3.5.1 Centroid Moment Tensor Solutions

To perform CMT inversions, we chose data from four stations of the YS network (Fig. 3.2b) in distance range of 150-200 km from the Alor earthquake sequence. Waveforms from closer stations were clipped, and waveforms of more distant stations were unable to be simulated with our local 1D model, due to strong lateral heterogeneity in the crust and uppermost mantle. Prior to the CMT inversion, we assessed the data quality and removed the noisy data. This involved removing the horizontal components of the MALK station and the vertical components of NOMU and TL07 to improve the waveform correlation fit (Figure 3.2a and 3.3a). The preferred new, local 1D velocity model (Fig. A.3) provided an overall higher fit to the selected four stations surrounding the events (waveform correlation at some components are $> 90\%$, Fig. 3.2a). To assess the 4D spatio-temporal grid search, we visualize our inversions in two plots: the depth-time and longitude-latitude diagrams. In both cases, the background color represents the fit between the real and the synthetic data interpolated at each point of the 4D spatiotemporal grid search (Fig. 3.2c, d).

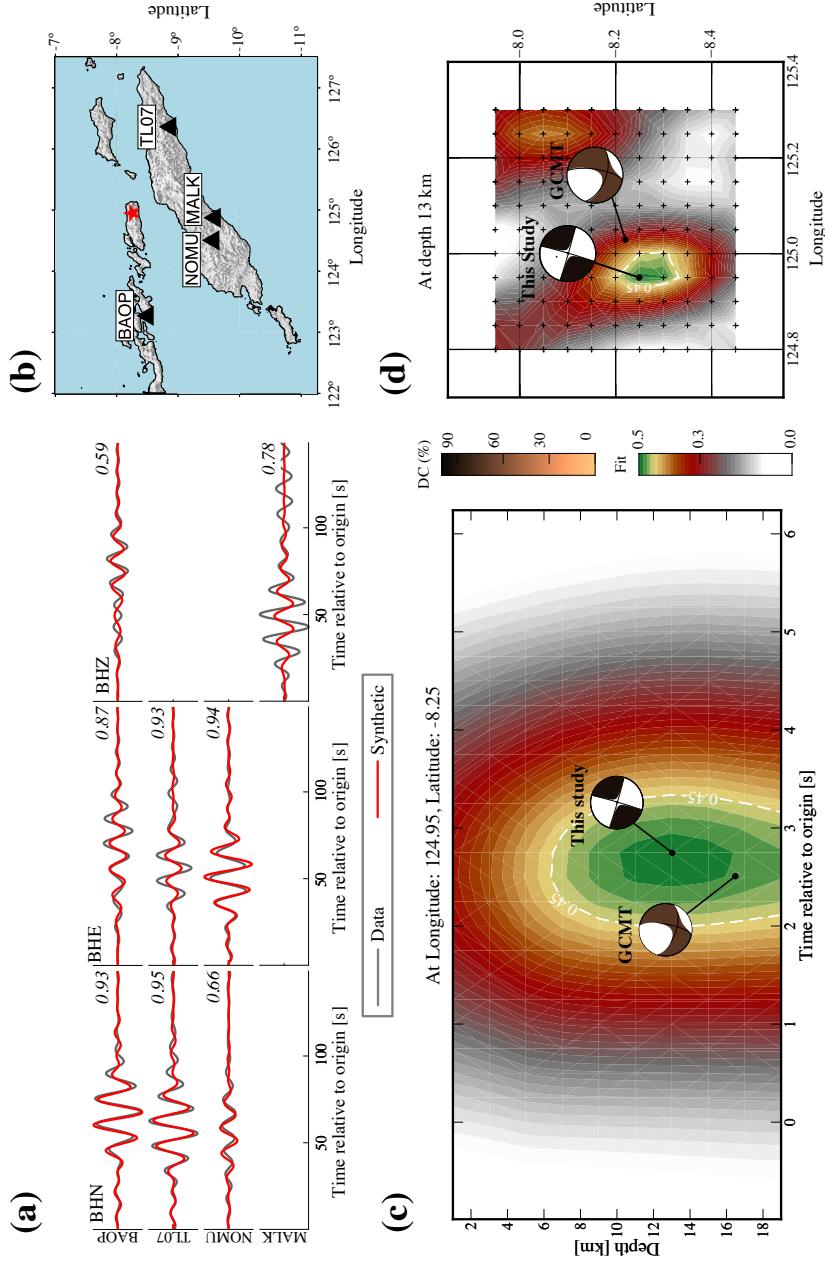


Figure 3.2: The centroid moment tensor solutions of the largest foreshock on 3 November 2015, performed on data filtered at 0.05–0.08 Hz. a) Waveforms correlation between the synthetic (red) and the observed (black) waveforms from four stations TL07, BAOP, NOMU, and MALK. The correlation values for each component are presented in the top right above the waveforms. b) Location of these four stations and the epicenter as reported by [GCMT](#). c) A time-depth slice through the 4D grid search of the centroid moment tensor solution at the optimum location of 124.95°E and 8.25°S. The background color represents the fit between the real and synthetic waveforms as described in Eq. 3.1 in the main text. d) Same as c) but for horizontal slice through the optimum depth of 13 km. The [GCMT](#) solution is plotted for comparison. The white dashed contour lines in c) and d) mark the threshold for the ‘family of solutions’ considered for the fault plane identification shown in Figure 3.4.

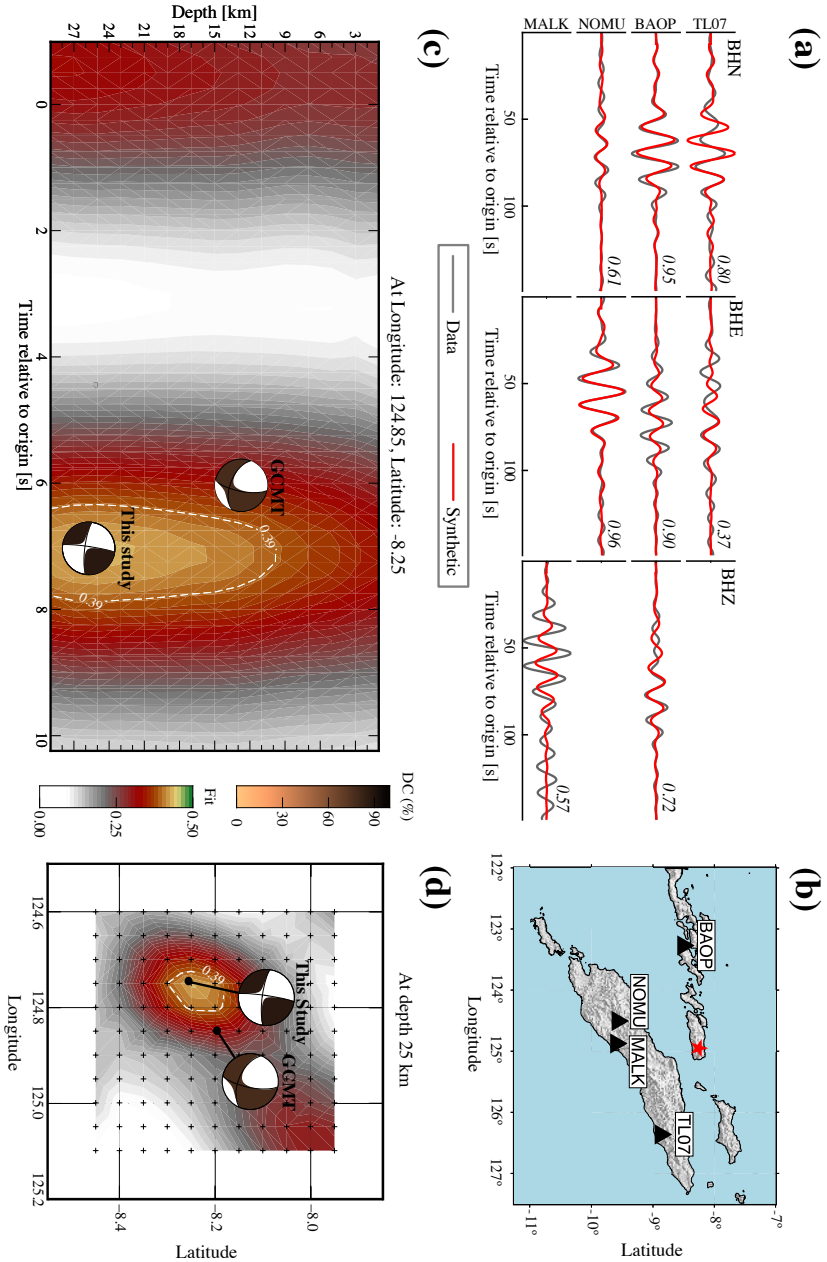


Figure 3.3: The centroid moment tensor solutions of the largest foreshock on 4 November 2015, performed on data filtered at 0.05-0.08 Hz. a) Waveforms correlation between the synthetic (red) and the observed (black) waveforms from four stations TL07, BAOP, NOMU, and MALK. The correlation values for each component are presented in the top right above the waveforms. b) Location of these four stations and the epicenter as reported by GCMT. c) A time-depth slice through the 4D grid search of the centroid moment tensor solution at the optimum location of 124.85°E and 8.25°S. The background color represents the fit between the real and synthetic waveforms as described in Eq. 3.1 in the main text. d) Same as c) but for horizontal slice through the optimum depth of 25 km. The GCMT solution is plotted for comparison. The white dashed contour lines in c) and d) mark the threshold for the 'family of solutions' considered for the fault plane identification shown in Figure 3.4.

We visualize the [CMT](#) inversion for the largest foreshock M_w 5.3, which occurred on 3 November 2015, at 21:25:02.00 UTC (Figure 3.2), and the main shock, M_w 6.2, which occurred on 4 November 2015, at 03:44:15.00 UTC (Figure 3.3). The optimum [CMT](#) solutions for both events show a strike-slip mechanism with near-vertical planes. The high [DC](#) percentage of both events ($> 85\%$) suggests a rupture on a simple planar fault. In comparison, the mechanisms reported by the [GCMT](#) show a strike-slip mechanism with a normal component and a lower [DC](#) percentage. The optimum centroid depth reported by [GCMT](#) is deeper by 3 km in the case of the foreshock but shallower by 13 km in the case of the mainshock. Such discrepancies in depth, location and MT components between studies performed using local or regional 1D or 3D models and [GCMT](#) are expected and have been documented in other studies (e.g., [Valentine and Trampert, 2012](#); [Hejrani et al., 2017](#); [White et al., 2019](#); [Hejrani and Tkalčić, 2019, 2020](#); [Mousavi et al., 2023](#)). At global or continental scales, the lateral heterogeneity of the Earth strongly affects the passage of surface waves, and if these heterogeneities are not considered in the calculation of the synthetics, then the [CMT](#) solutions would be affected (e.g., [Hjörleifsdóttir and Ekström, 2010](#); [Valentine and Trampert, 2012](#); [Hejrani et al., 2017](#); [Zhang et al., 2022](#)). At regional distances, 3D models (e.g., [Hejrani and Tkalčić, 2019, 2020](#); [Donner et al., 2020](#); [Yamaya et al., 2022](#); [Liu et al., 2022](#); [Song et al., 2022](#)) or 1D average models driven for a specific region of interest (e.g., [Zahradnik et al., 2008](#); [Tkalčić et al., 2009](#); [Lister et al., 2018](#); [Mustać et al., 2020](#)) have shown success in fitting the data up to 0.1 Hz. This is the case with our [CMT](#) inversion using the 1D velocity model developed from local earthquake data.

3.5.2 Hypocenter location

The first arrivals of P- and S-waves carry information from the rupture initiation and by locating the earthquakes, we can estimate the time and location where the rupture initiates. We manually picked P- and S-arrival times of the largest foreshock

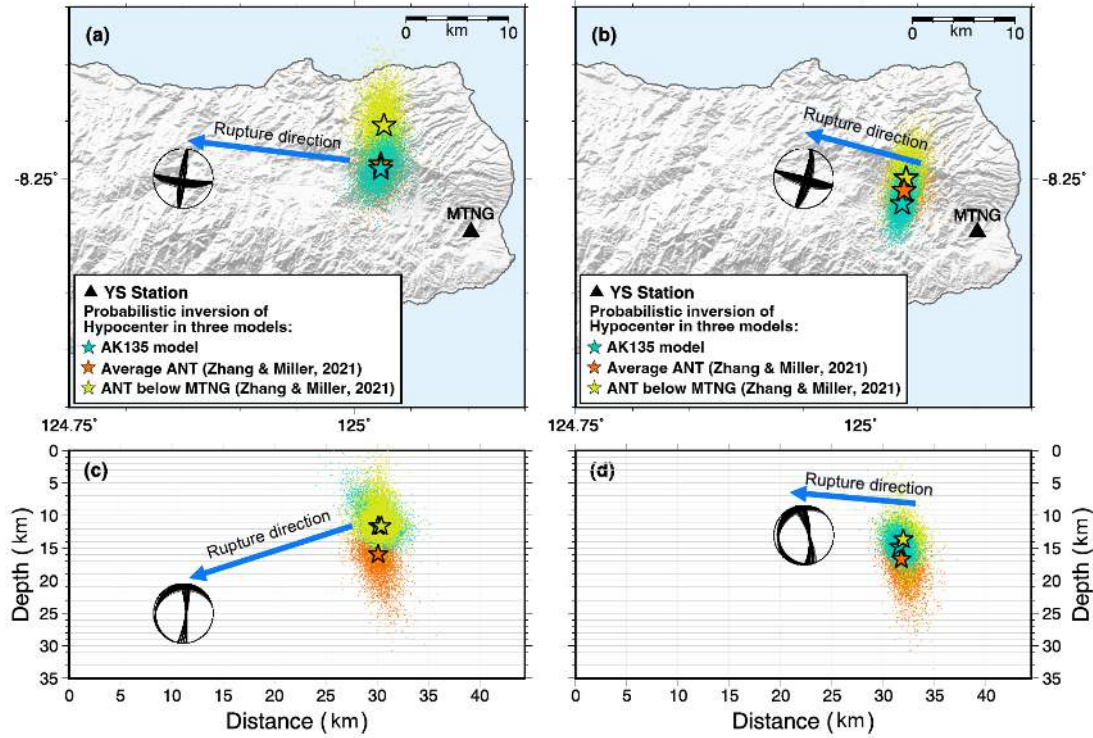


Figure 3.4: Fault plane identification for two earthquakes using the H-C method (Zahradnik et al., 2008). The hypocenter (H) solution for the mainshock (4 November 2015, at 03:44:15.00 UTC) in panel a) and c), and the largest foreshock (3 November 2015, at 21:25:02.00 UTC) in panel b) and d) determined using three different 1D velocity models, indicated by colored stars (see Section 3.4.4 for further details). The hypocenter indicates consistent alignment with the west-north-west striking nodal planes from the a) mainshock and b) the largest foreshock. The 1D velocity models used here are shown in Fig. A.3. East-west cross section through the family of solution for CMT and probabilistic solutions for H is shown for c) the mainshock and d) the largest foreshock. Blue arrows indicate the inferred direction of the rupture based upon H-C. Both events show a similar strike-slip mechanism.

and the main shock and used the NonLinLoc software (Lomax et al., 2000, 2009) to relocate them. The hand-picked P- and S- arrivals for both events are shown in the Supplementary Materials (Figure A.1 and A.2). As mentioned earlier, we use the Oct-Tree algorithm implemented in NonLinLoc to search the model space and relocate the earthquakes in a nonlinear probabilistic framework. The advantage of this approach is that it provides uncertainty on the location and origin time of the events, as well as the residuals between the observed and the synthetic data. Our location uncertainties are shown by density plots (Figure 3.4) obtained by drawing

samples from PDFs calculated in the Oct-Tree algorithm. The number of samples are proportional to the probability (Lomax et al., 2000). The final hypocenter location is determined by its maximum-likelihood value (stars in Figure 3.4). We repeated the hypocenter estimation in three velocity models to assess the effect of the Earth model on the results (Figure 3.4).

We repeated the inversion with and without the arrivals that had large residuals (> 1 second). We observed residuals > 6 seconds for both events at stations TL1B, TL08, and SINA for all the 1D velocity models we tested, therefore we removed these stations from the inversion process.

Our locations for the mainshock and the largest foreshock closely match the location in Jiang et al. (2022), however we obtained a much lower uncertainty with horizontal and vertical errors of ± 3 km. This is attributed to an improved local 1D velocity model and more accurate manual picks. It seems that the rupture was initiated at depth range of 12-17 km for both events (Figure 3.4).

3.5.3 Fault-Plane Determination

For both earthquakes, following (Zahradnik et al., 2008), we determined the fault plane in the focal mechanism by examining the nodal plane that encompasses both H and C. In this approach, the H provides additional information required to resolve the ambiguity in the nodal planes derived from the CMT solution. The assumptions made with this approach are that H and C are sufficiently separated (i.e., the rupture is longer than the individual uncertainty of H and C) and that the rupture occurs on a planar fault. The two earthquakes here have a DC% of > 85 , indicating a relatively simple rupture on a planar fault. To incorporate an assessment of uncertainty for C and the nodal planes, ‘a family of solutions’ is considered instead of one solution with best fit to the data. This family solution is chosen from the 4D spatiotemporal grid search assuming a threshold waveform fit, following (Hejrani and Tkalčić, 2020). All solutions with waveform fit above 90% of the optimum point are chosen. We

outlined these solutions with a white dashed line in Figure 3.2 & 3.3 for the foreshock and the mainshock, respectively. By visualizing H , C , and the nodal planes, and considering their uncertainties, we derive the northwest-southeast plane to be the fault plane for both events (Figure 3.4a, b). The fault plane of the foreshock strikes at $106.2^\circ \pm 7.6^\circ$ and the fault plane of the mainshock strikes at $97.1^\circ \pm 4.6^\circ$, indicating a difference of $9.1^\circ \pm 3^\circ$. Moreover, the rupture seems to be propagating towards the surface for the foreshock (Figure 3.4d), while it is propagating deep in the case of the mainshock (Figure 3.4c).

3.6 Discussion

Alor island is an orogenic product of the Banda arc, where the Australian Plate is subducted underneath the Eurasian Plate. Currently, the region is undergoing arc-continental collision, and Alor is located between the inner arc bounded by the back-arc thrust in the north and the Wetar suture zone in the south. Despite being in such an active tectonic setting, the island of Alor has not experienced many significant damaging earthquakes. However, the late 2015 earthquakes were some of the most recent notable seismic events recorded on the Island.

3.6.1 Rupture Pattern

The rupture pattern of the foreshocks, mainshock and aftershocks of the 2015 Alor earthquake sequence appear simple in the map view. However, with depth, the sequence of events has an interesting rupture pattern. First, a large number of small earthquakes, followed by foreshocks as big as M_w 5.3, occurred in the hours before the main event. Most of these events originated in a small region to the east of the island (around 125° E and -8.5° S) at depths of ~ 10 km. Second, the hypocenter depth of the majority of the events, including the mainshock, is concentrated at depths of 0-10 km (Figure 3.5b). However, our CMT solution shows that the centroid depth of the mainshock extends as deep as 25 km.

The lack of aftershock activity on segments of a fault that have ruptured during the mainshock have been observed and reported in previous studies (e.g., Gallovič et al., 2009; Das and Henry, 2003; Liu et al., 2003; Chiaraluce et al., 2003, 2011; Gülen et al., 2002; Yin et al., 2018). Gallovič et al. (2009) showed the absence of aftershocks in the area where the maximum moment was released during the 2008 M_w 6.3 Movri Mountain earthquake in Greece. The majority of the aftershocks were concentrated towards the two ends of the fault segments that experienced the largest moment release. In the case of Alor, a similar pattern is seen but in depth. Another distinctive feature of the Alor sequence is that the fault plane of main shock strikes at $\sim 9^\circ$ difference compared to the strike-slip aftershocks and foreshocks, indicating that the fault system exhibits different strike characteristics at deeper depth.

The spatial and temporal separation of the H and C are consistent with rupture velocity of 2.8 – 3.2 km/s for the mainshock and the largest foreshock. For the mainshock, the spatial separation between H and C is $\sim 20 - 21$ km (Fig. 3.4c) and given the centroid time of +7 s (Fig. 3.3c, relative to the hypocenter time), the rupture velocity of $\sim 2.8 - 3.0$ km/s could be deduced. In the case of the foreshock, the H-C separation is $\sim 8 - 9$ km (Fig. 3.4d) and the centroid time is 2.8 s (Fig. 3.2c), resulting in an estimation of rupture velocity of 2.8 – 3.2 km/s. The centroid moment tensor solutions for the foreshocks and aftershocks indicate strike-slip mechanisms with small variation in strike (Table 3.1, Fig. A.4-A.10), except for aftershocks A1 and A3 (Figure 3.5a). The aftershock solution, A1 is dominated by the thrust mechanism, with a strike trending northeast-southwest, whereas the solution for A3 is primarily characterized by the normal component, albeit with a small strike-slip component. These focal mechanism solutions reflect the local geological setting, considering that the rupture occurred northwest of Alor along a known fault that separates the northwestern peninsula from the main island (Silver et al., 1983; Burhan et al., 1997). The P-axis (the maximum principal stress) trends a west-northwest direction, in agreement with the interpretation of the dominant tectonic force (Masson et al., 1991) and

the fault plane solutions observed in the northwest of Wetar ([McCaffrey, 1988](#)).

3.6.2 Regional tectonics

Earlier studies of surface expressions of faults in the eastern Sunda region were based on airborne radar data obtained during a marine geophysical investigation by [Silver et al. \(1983\)](#). Their interpretation of the Side Looking Airborne Radar ([SLAR](#)) data of Alor Island pointed out two additional parallel faults trending west-north-west ([Silver et al., 1983](#)). However, no further survey or analysis was provided. Nonetheless, their [SLAR](#) interpretation of the fault orientation aligns with our observed strike-slip foreshock and aftershocks, although it differs slightly ($\sim 9^\circ$) from the mainshock.

In a more recent study on Alor Island, [Funning and Garcia \(2019\)](#) used Interferometric Synthetic Aperture Radar ([InSAR](#)) to investigate the main event presented in our study. They processed the ascending data from Sentinel-1IW and descending data from Advanced Land Observing Satellite ([ALOS-2](#)) to identify peak deformation and the likely location of the fault, which is represented by a black line in Figure 3.5a. The fault, which trends southeast-northwest, is visible on their [InSAR](#) image and is remarkably consistent with the strike of aftershocks (Figure 3.5). The centroid location of the mainshock is a few kilometers south of the proposed fault trace near the surface, which is consistent with both the deeper centroid depth of the mainshock and the small south dipping angle of its fault plane. Furthermore, the passes of satellites includes the timespan in which many of the earthquakes occurred. Therefore the deformation inferred from [InSAR](#) includes the cumulative displacement from all of the earthquakes over a time period between the satellite orbits (48- and 450-day timespan in the case of [InSAR](#) data used for Alor study; [Funning and Garcia, 2019](#)). As the histogram of the earthquake depths shows (Fig. 3.5b) most events occur as foreshocks and aftershocks at depth < 10 km, which are the main contributions to the [InSAR](#) images.

Table 3.1: Nine Moment Tensor solutions from the 2015 Alor earthquake sequence. The table includes centroid time, location (longitude and latitude), depth, moment magnitude values, and Double-Couple (**DC%**). The corresponding values of **GCMT** and this study are denoted as G and R, respectively.

ID	Event Date	Origin Time	Centroid Time	Longitude (deg)	Latitude (deg)	Depth (km)	M_w	DC%	RCMT solution	GCMT solution
F1	2015-11-01	16:50:59.00	16:51:01.75	124.95	-8.25	13.0	4.00	87.6		
F2	2015-11-03	20:54:44.00	20:54:45.75 (R)	124.95 (R)	-8.25 (R)	13.0 (R)	4.57 (R)	96.5		
			20:54:44.90 (G)	125.00 (G)	-8.27 (G)	13.9 (G)	4.86 (G)			
F3	2015-11-03	21:25:02.00	21:25:04.50 (R)	124.95 (R)	-8.25 (R)	13.0 (R)	5.31 (R)	85.8		
			21:25:04.75 (G)	125.03 (G)	-8.22 (G)	16.0 (G)	5.57 (G)			
F4	2015-11-04	04:34:03.00	04:34:06.25	125.95	-8.15	3.0	4.50	82.8		
F5	2015-11-04	08:14:57.00	08:15:01.25	125.05	-8.30	15.0	4.40	72.0		
M	2015-11-04	03:44:15.00	03:44:22.00 (R)	124.85 (R)	-8.25 (R)	25.0 (R)	6.23 (R)	89.3		
			03:44:21.00 (G)	124.95 (G)	-8.20 (G)	12.0 (G)	6.47 (G)			
A1	2015-11-05	16:24:13.00	16:24:14.75	124.70	-8.15	3.0	4.55	72.2		
A2	2015-12-19	22:37:59.00	22:38:02.50	124.95	-8.30	13.0	4.03	67.6		
A3	2016-03-25	17:01:57.00	17:02:00.00	125.10	-8.35	11.0	3.94	76.7		

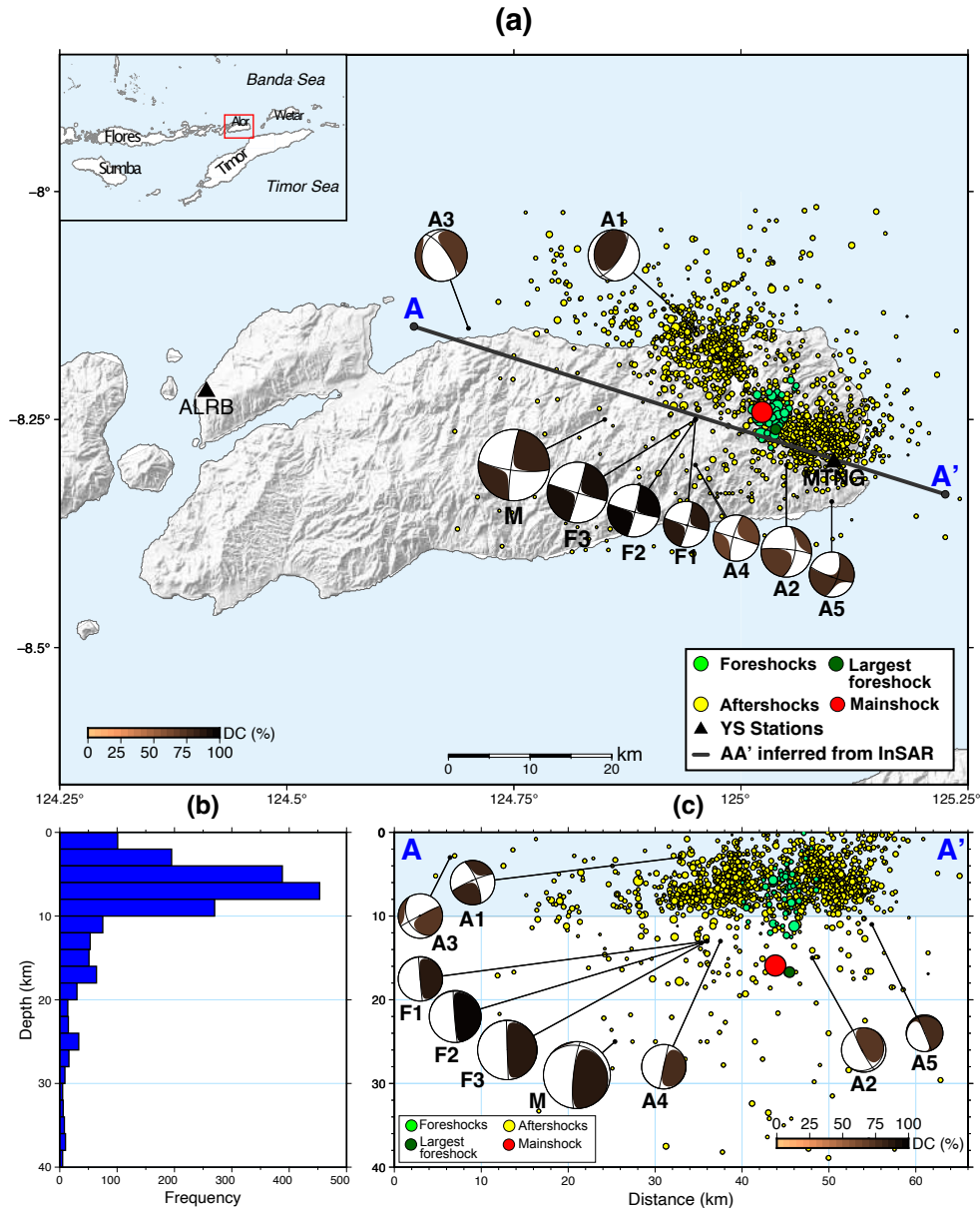


Figure 3.5: a) Map view of the [CMT](#) solutions (Table 3.1) with the epicenters of events in the sequence relocated by [Jiang et al. \(2022\)](#). F#: Foreshock, M: Main event, A#: Aftershock. The largest foreshock (dark green) and the mainshock (red) are two events that were manually relocated in this study. The black line (A-A') represents the inferred fault trace based on the [InSAR](#) study by [Funning and Garcia \(2019\)](#). b) The histogram shows the depth distribution of hypocenters in the sequence from [Jiang et al. \(2022\)](#) catalog. c) The cross-section AA' displays earthquake data from the catalog ([Jiang et al., 2022](#)) represented by colored circles projected onto the 30 km-wide profile. Foreshocks and aftershocks are shown in green and yellow circles, respectively. The light blue rectangle in Fig. 3.5c represents the depth range of the majority foreshocks and aftershocks, within the upper 10 km depth as shown in the histogram b.

A recent [CMT](#) study calculated focal mechanism for 20 events beneath the Sunda-Banda Arc transition, including the largest foreshock in the Alor sequence and the mainshock ([Supendi et al., 2022](#)). Although the general strike-slip mechanism of their solutions is similar to ours, they infer a northeast-southwest striking fault plane, which is inconsistent with the relocated aftershock distribution from [Jiang et al. \(2022\)](#), our fault plane identification using H-CMT analysis and the [InSAR](#) data. The centroid location of the [CMT](#) solution for the largest foreshock from [Supendi et al. \(2022\)](#) is located offshore, northeast of Alor Island, which they used to infer a NE-SW strike. Such discrepancies between centroid location, and MT components in [CMT](#) solutions in different catalogs have been reported in other studies and the choice of Earth models ([Šílený, 2004](#); [Cesca et al., 2006](#)), station coverage ([Cesca et al., 2006](#); [Ford et al., 2010](#); [Vera Rodriguez et al., 2011](#)) and frequency band ([Hejrani and Tkalčić, 2020](#); [Sokos and Zahradník, 2013](#)) are discussed and well-documented in the literature. Our H-CMT fault model is superior as it is using a local 1D Earth model developed for this region as well as data from a local network that surrounds the event.

The tectonic setting of Alor Island also supports the southeast-northwest rupture trend which has been discussed previously in the structure and tectonics literature ([Silver et al., 1983](#); [McCaffrey and Nábělek, 1984](#); [Breen et al., 1989](#); [Masson et al., 1991](#)). Despite the collision of the Australian continent northward acting as the main tectonic force, it does not support the offset of Wetar Island. [Masson et al. \(1991\)](#) suggested that the translation of the Wetar Island (Figure 3.1) was attributed to the internal deformation of the Banda Sea, with the force coming from the northwest to the southeast, instead of the north-south direction. The translation, which resulted in 50 km gap between Alor and Wetar, is also accommodated by a series of fault systems. In particular, a relatively wide fault zone with a strike-slip mechanism located in the east and west of Atauro Island, trending in northerly direction. The change in trend, transitioning from a northerly direction off Wetar to a north-easterly

direction off Timor, aligns with the absence of compression or shortening along the north coast of Timor. On a larger scale, a shortening in the upper plate due to the movement of the Australian Plate may be transferred to the back-arc through faults that appears across the entire arc and through Timor. The Belu fault is one such fault that cuts across Timor and connects to the northern fault system ([Charlton et al., 1991](#); [Kaneko et al., 2007](#)).

3.7 Conclusions

In conclusion, we computed nine centroid moment tensor solutions of the 2015 Alor earthquake sequence using a set of stations from the YS network and estimated the stability of the centroid location and nodal planes following [Hejrani and Tkalčić \(2020\)](#). We also determined the hypocenter, fault plane, and rupture direction for the largest foreshock and the main event. To identify the fault plane, we utilized the approach proposed by [Zahradnik et al. \(2008\)](#), which examines the geometrical locations of the hypocenter and centroid for the nodal planes obtained from the moment-tensor solution (i.e., the fault plane and the auxiliary plane). We incorporated the stability of the CMT solution and the hypocenter solution in our fault plane analysis following [Mousavi et al. \(2023\)](#). Our results depict an interesting rupture pattern at depth for the Alor earthquake sequence in 2015: A significant occurrence of small earthquakes concentrated in a specific region to the east of the island at depth ~ 10 km led to the mainshock which ruptures deep down to 25 km. The majority of the aftershocks migrate back to the top 10 km. The lower crust experienced full stress release during the mainshock, while the upper 10 km.

3.8 Data and Resources

The full waveforms and metadata of the YS array used in this study are archived and accessible through the Incorporated Research Institutions for Seismology Data Man-

agement Center ([IRIS-DMC](#)) and the AusPass server https://www.fdsn.org/networks/detail/YS_2014/, last accessed May 2023. The earthquake catalog used to produce figures in this study was obtained from AusPass http://auspass.edu.au/research/banda_arc.html as published in [Jiang et al. \(2022\)](#). The Global Centroid Moment Tensor Project database was accessed through <https://www.globalcmt.org/CMTsearch.html> (last accessed in February 2023). The information about Global CMT is available at globalcmt.org (last accessed May 2023).

Supplemental material for this article includes Figure [A.1-A.10](#).

3.9 Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest or competing interests recorded.

3.10 Acknowledgments

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New Insights Into Crustal Deformation of the Indonesia–Australia–New Guinea Collision Zone From a Broad-Scale Kinematic Model

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S. Zhao,¹ S. McClusky^{1,2}, P. R. Cummins^{1,2}, M. Miller¹, and H. Nugroho¹

Foreword

In Chapter 4, we characterize and quantify deformation across the Indonesia–Australia–New Guinea subduction and collision system, with particular emphasis on the central Banda Arc and its eastern transition zone. This analysis builds directly on Chapter 3, which examined the manifestation of regional collision on the island of Alor. Alor lies within the Timor Block as delineated by Bird (2003) and supported by subsequent GPS-based studies (e.g., Nugroho et al., 2009; Koulali et al., 2016), and therefore provides an important local-scale expression of broader plate boundary processes.

Previous studies using earthquake moment tensor solutions have shown that de-

¹Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia.

²Geoscience Australia, Symonston, ACT, 2609, Australia.

formation within the Banda forearc is complex, involving both shortening parallel to plate convergence and extension perpendicular to it (McCaffrey, 1988; McCaffrey and Abers, 1991). These observations have been interpreted as evidence for arc-parallel transport and extrusion within the forearc, with early models suggesting that outward extrusion of the Banda Arc may drive thrusting at the Aru Trough.

Our detailed analysis of the 2015 Alor earthquake sequence provides new seismological evidence supporting this framework. In particular, the results indicate intra-Timor Block transport of at least one large crustal block (including northeast Alor and Wetar) moving eastward along the leading edge of the semi-accreted arc-collision zone, relative to southern Alor. This interpretation is consistent with field-based observations from Timor-Leste (e.g., Duffy et al., 2013), which also suggest significant along-arc transport within the collision system.

To understand the drivers of such internal deformation within the Timor Block (addressed in Chapter 5), it is first necessary to place these observations in a broader geodynamic context. In particular, the Banda Arc represents a striking example of oroclinal bending, where the geometry and kinematics of the arc are shaped by subduction rollback into the Banda Embayment. This process likely involves both east–west rollback associated with the Weber Deep and north–south rollback within the South Banda Sea, accompanied by low-angle detachment faulting that feeds thrusting at the Aru Trough (e.g., Pownall et al., 2016). As a consequence, the forearc undergoes significant along-arc stretching and segmentation, facilitating arc-parallel motion.

Finally, the Banda orocline is not only bounded by the Timor collision zone to the west, but also by the complex Papuan collision zone to the northeast. Understanding the present-day kinematics along this northern continental boundary of the Australian Plate is therefore essential for interpreting how the margin has evolved, and continues to reorganize, in response to ongoing subduction and consumption of oceanic lithosphere within the Banda Embayment.

Motivated by these regional dynamics, we integrate GPS observations from previously published datasets with new campaign data collected in Timor-Leste. Combined with regional fault geometries and slip vector constraints, we invert these data to derive a best-fitting kinematic model consisting of 23 elastic blocks, including estimates of block rotations and slip rates along their boundaries. Our results provide new insight into the distribution of deformation across the region, including the formation of the Cenderawasih Bay sphenochasm,¹ which we interpret as resulting from a combination of Bird's Head Block rotation and southwest-directed convergence along the Lowlands Fault. Furthermore, the estimated slip vectors along the New Guinea Fold-and-Thrust Belt reveal a systematic transition in tectonic style, from predominantly thrust faulting in the west, to sinistral motion in the central segment, and back to thrust faulting in the east, highlighting the influence of multiple, interacting geodynamic drivers.

4.1 Abstract

The Indonesia-Australia-New Guinea collision zone comprises a complex system of tectonic blocks whose relative motion accommodates convergence of the Sunda Block, Pacific, Australian, and Philippine Sea plates. Previous studies have considered either the western or eastern ends of this system, in eastern Indonesia and Papua New Guinea, respectively. However, these studies had limited ability to characterize either the kinematics of the central part of the system or transitions in tectonic regime across it. In this study, we perform a simultaneous inversion of 492 earthquake slip vectors and 267 GPS velocities to quantify the block movement spanning the Sunda-Banda Arc, Western New Guinea, and Papua New Guinea. Our best-fitting kinematic block model comprises 23 elastic blocks, for which we estimate the rotation rates and block boundary slip rates. We show how the Cenderawasih Bay sphenochasm was

¹A wedge-shaped gap at the intersection of structural planes. See Powell (1987), s.v. "Sphenochasm," https://doi.org/10.1007/3-540-31080-0_101.

likely formed by a combination of both rotations ($2.82 \pm 0.11^\circ/\text{Myr}$ anticlockwise) of the Bird's Head Block and southwest-directed convergence ($39.9 \pm 1.7 \text{ mm/yr}$) along the Lowlands fault. Our estimated relative slip vectors across the New Guinea Fold-and-Thrust Belt indicate a transition in the tectonic regime of the block boundary from predominately thrust faulting at its western segment, with a convergence rate up to $19.5 \pm 0.6 \text{ mm/yr}$, to predominately sinistral motion in the center segment with slip rate $\sim 7 \text{ mm/yr}$, and returning to thrust in the eastern segment with a convergence rate up to $9.0 \pm 0.5 \text{ mm/yr}$, implying the combined effect of multiple driving mechanisms.

Key Points

- A new broad-scale kinematic model has been developed spanning the 5,000 km length of the Indonesia–Australia–New Guinea collision zone
- The evolution of Cenderawasih Bay is based on the joint effect of the rotation of the Bird's Head block and the WSW drift of Weyland Thrust
- The New Guinea Fold-and-Thrust Belt experiences two transitions in its tectonic regime, as it traverses the center of the collision zone

Plain Language Summary

The Indonesia–Australia–New Guinea collision zone is an east-west elongated belt of complex tectonics at the northern edge of the Australian Plate, where the northward movement of the Australian continental lithosphere is accommodated by relative movement among a series of “microplates” in Indonesia and New Guinea. The interactions among these plates span the full gamut of tectonic phenomena. In this study, we use [GPS](#) measurements of crustal motion and earthquake data to estimate the motion of the tectonic units (plates and microplates) within the collision zone. While previous studies have considered either the western or eastern parts of this collision zone in isolation, in this study we consider together all the blocks spanning the zone from west to east. We show that this provides greater insight into

changes in the tectonic regime through the center of the collision zone, and allows us to establish a new model for the development of the Cenderawasih Embayment in north-central New Guinea.

4.2 Introduction

We define the Indonesia–Australia–New Guinea collision zone ([IANGCZ](#)) as the area where the Australian, Philippine Sea, and Pacific Plates and the Sunda Block, all converge (Figure 4.1). The [IANGCZ](#) comprises the eastern islands of the Indonesian archipelago, the island of New Guinea (the Indonesian provinces of West Papua and Papua, and Papua New Guinea ([PNG](#)), and the northern edge of continental Australia. The [IANGCZ](#) is characterized by rapid oblique convergence, resulting in complex orogenesis, frequent earthquakes, and volcanic activity (Figure 4.1; Figure 4.2; [Baldwin et al., 2012](#); [Bock et al., 2003](#); [Hamilton, 1979](#); [Koulali et al., 2015, 2016](#); [Puntodewo et al., 1994](#)).

Regions with active tectonic activity like the [IANGCZ](#) are often delineated in global plate models as “deforming zones” ([Kreemer et al., 2014](#)) or “orogens” ([Bird, 2003](#)), for which crustal motion data are excluded from the determination of the otherwise rigid plate motion. Even as early as the 1970s, however, it was recognized that such areas of deformation are often themselves usefully described in terms of discrete “microplates” (e.g., [Alvarez et al., 1974](#); [Dewey et al., 1973](#)), relatively small-scale blocks with little internal deformation except near their edges, where much higher strains are experienced relative to the microplate interiors. While imperfect—microplate boundaries may be difficult to define, and their interiors are not perfectly rigid—kinematic microplate models have proven useful in interpreting crustal motion and earthquake data in many regions worldwide (see [McCaffrey et al., 2002](#)), for a useful overview with examples from Sumatra, Oregon, and Costa Rica). It is the approach we use in this study, building on the many previous studies that have used it to describe different parts of the [IANGCZ](#).

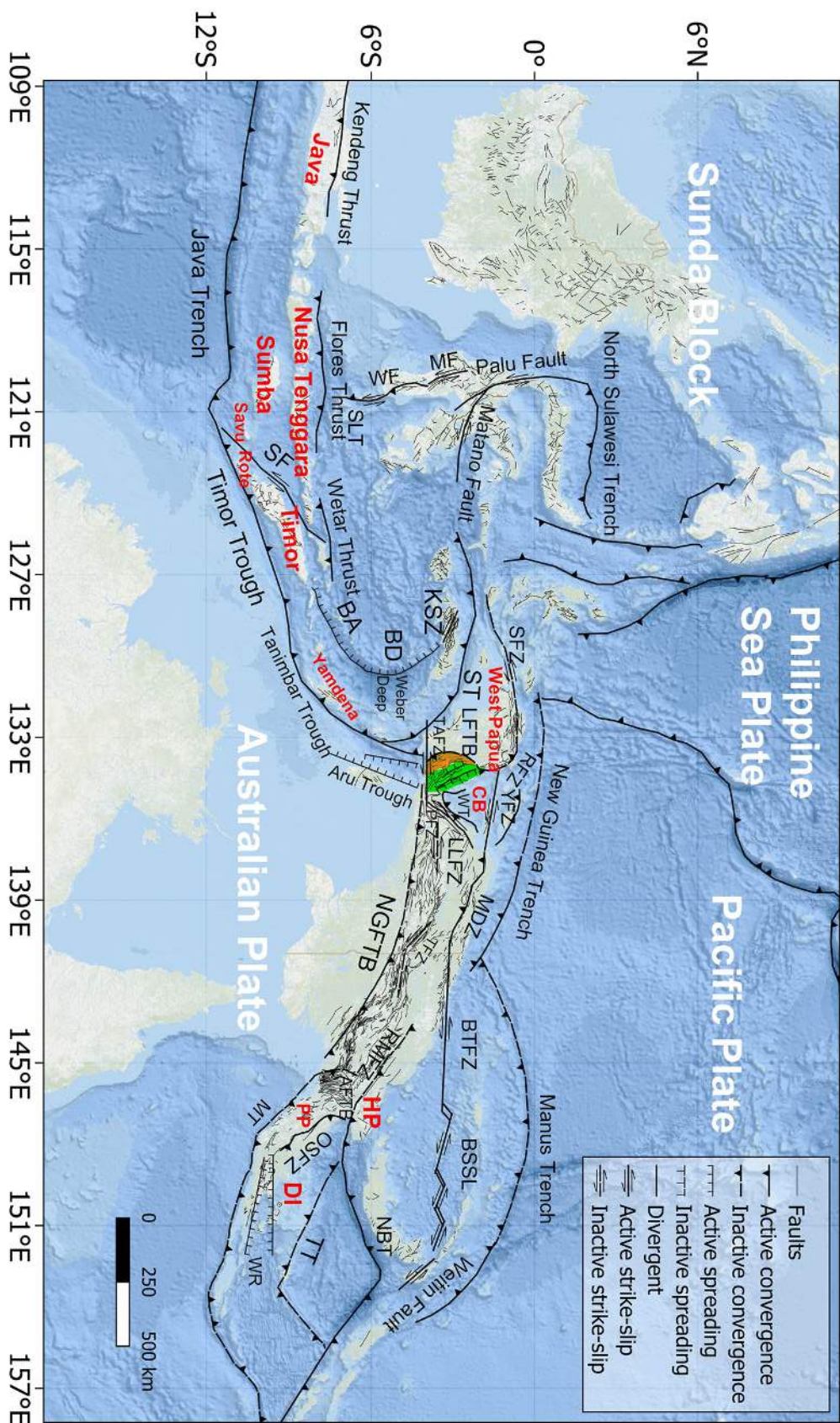


Figure 4.1: Topography and tectonic map of Indonesia–Australia–New Guinea collision zone. Tectonic boundaries are derived from Baldwin et al. (2012); Chen et al. (2019); Cloos et al. (2005); Cummins et al. (2020); François et al. (2016a); Jaya and Nishikawa (2013); Koulali et al. (2015), and Spencer et al. (2016). (Continued on next page.)

Figure 4.1: (Continued). Faults are from the East and Southeast Asia (CCOP) 1:2,000,000 geological map (downloaded from <https://www.orr-bodies.com/resource/ccop-geology-south-east-asia/>). AFTB: Aure Fold-and-Thrust Belt; BSSL: Bismarck Sea seismic lineation; BTFZ: Bewani-Torricelli fault zone; BA: Banda Arc; BD: Banda Detachment; CB: Cenderawasih Bay; DI: D'Entrecasteaux Islands; HP: Huon peninsula; KSZ: Kawa Shear Zone; LFTB: Lengguru Fold-and-Thrust Belt; LFZ: Lagaip fault zone; LLFZ: Lowlands Fault; NBT: New Britain Trench; MDZ: Mamberamo deformation zone; MF: Masupu Fault; MT: Moresby Trough; NGFTB: New Guinea Fold-and-Thrust Belt; OSFZ: Owen Stanley fault zone; PFZ: Paniai fault zone; PP: Papuan peninsula; PTFB: Papuan thrust-and-fold belt; RFZ: Ransiki fault zone; RMFZ: Ramu-Markham fault zone; SF: Semau Fault; SFZ: Sorong fault zone, SLT: Selayar Trough; ST: Seram Trench; TAFZ: Tarera-Aiduna fault zone; TFZ: Tahin fault zone; TT: Trobriand Trough; WR: Woodlark Rift; WF: Walanae Fault; WT: Weyland Thrust; YFZ: Yapen fault zone. The green patch represents the internal zone of Lengguru fault, and the dark orange patch represents the external zone of the Lengguru fault, showing different tectonic regimes.

Most early kinematic studies of the IANGCZ were based on earthquake and geologic data (Fitch, 1970, 1972). The first GPS measurements took place in 1991, and early studies of GPS velocities provided preliminary broad-scale estimates of relative motion between the major plates—the Australian and Pacific plates, and the Sunda Block (Puntodewo et al., 1994; Socquet et al., 2006; Stevens et al., 2002; Tregoning et al., 1994). With the ongoing development and full deployment of the GPS space segment, improvements in GPS receiver technology, and continual reductions in GPS receiver costs, more detailed GPS-based studies of microblock motions were possible. Studies in the 1990s and 2000s delineated the microblock motions of either the western part of the IANGCZ in eastern Indonesia (Bock et al., 2003; Koulali et al., 2016, 2017; Nugroho et al., 2009; Puntodewo et al., 1994; Simons et al., 2007; Socquet et al., 2006; Stevens et al., 2002; Tregoning et al., 1994), or the eastern part in Papua New Guinea (Biemiller et al., 2020; Koulali et al., 2015; Tregoning, 2002; Tregoning et al., 1998a, 2000; Wallace et al., 2004, 2014). However, as indicated in Figure 4.1, several major faults extend from the western to the eastern part of the IANGCZ, and these are likely associated with large-scale deformation affecting both regions. Without considering the full breadth of the IANGCZ, previous kinematic models cannot fully and accurately characterize changes in tectonic regimes along such faults.

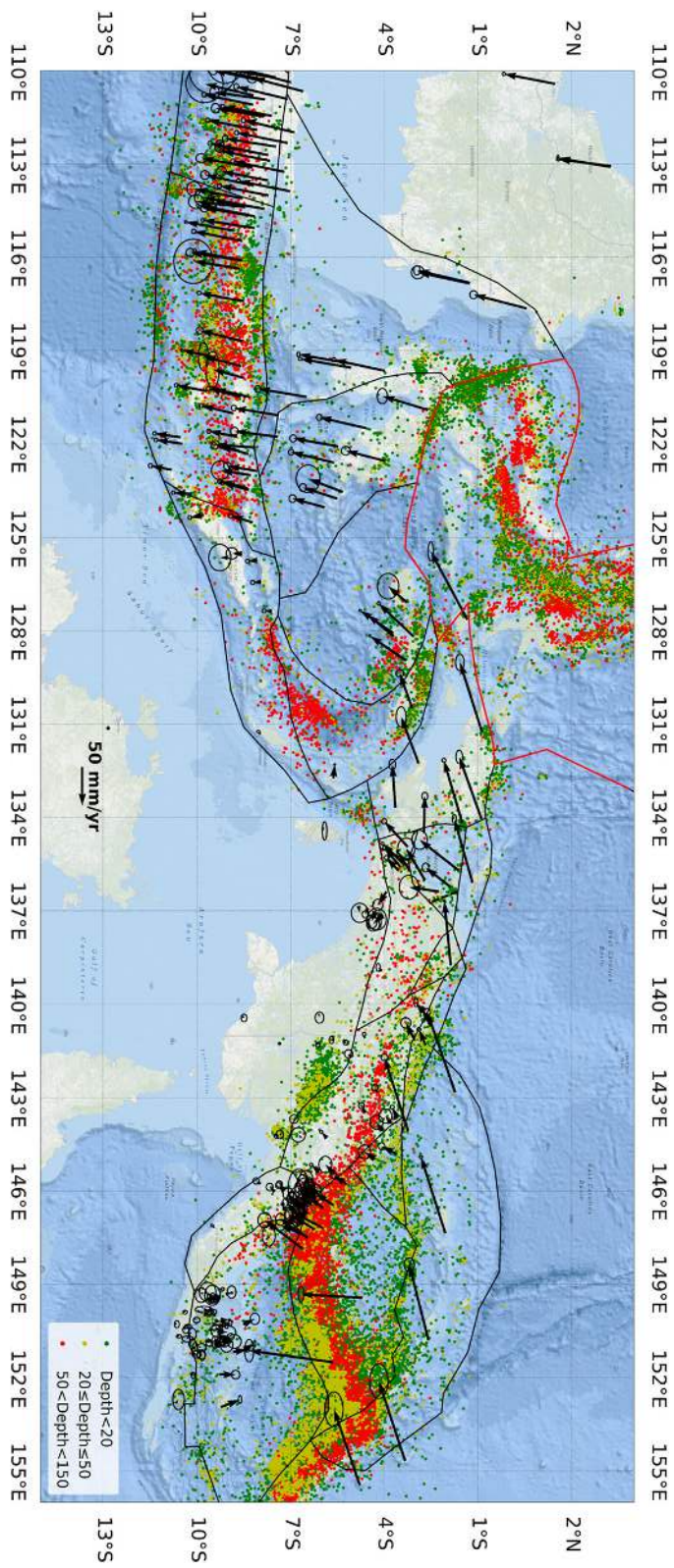


Figure 4.2: The GPS velocity field with 95% confidence interval ellipses was utilized in this study with respect to the Australian Plate. The names of the GPS sites are shown in Table B.1 of Supporting Information B. (Continued on next page.)

Figure 4.2: (Continued). In the Sunda-Banda region and West New Guinea, the relocated seismicity data ($M_w \geq 5$) are derived from [Supendi et al. \(2020b\)](#) from 2009 to 2018, with depth of less than 150 km. In the Papua New Guinea area, the relocated seismicity data ($M_w \geq 5$) are derived from the [ISC Bulletin](#) catalog with the same time and depth range. The solid red lines represent the free-slipping boundaries (locking constrained to zero); the solid black lines represent the block boundaries.

In addition, in the central part of the [IANGCZ](#)—the Indonesian provinces of Papua and West Papua, as well as western [PNG](#)—the kinematic studies are fewer and mainly focus on the Bird’s Head region or regard all of Western New Guinea as a single block, due to the lack of data and the remoteness of the region (e.g., [Bock et al., 2003](#); [Pubellier and Ego, 2002](#); [Stevens et al., 2002](#)). The paucity of [GPS](#) data to constrain detailed kinematic models in the Banda Sea and West New Guinea led to a wide-ranging debate on the origin and mechanism of the tectonic structures in this area. For example, the tectonic evolution of Cenderawasih Bay ([Babault et al., 2018](#); [Charlton, 2000a, 2010](#); [François et al., 2016b](#)); along-strike changes in motion along the New Guinea Fold-and-Thrust Belt (New Guinea Fold-and-Thrust Belt ([NGFTB](#)); [Baldwin et al., 2012](#); [Cloos et al., 2005](#); [Hill and Hall, 2003](#)) and the driving mechanism of some highly active faults (like the Tarera-Adiuna fault, Lengguru fault, and Seram Trough; [Bailly et al., 2009](#); [Baldwin et al., 2012](#); [Cloos et al., 2005](#)). These studies are mainly based on geological and seismic data, and the deformation in this complex plate boundary zone has not been well quantified. Due to the lack of [GPS](#) measurements, it is difficult to determine the micro-block boundaries of a more sophisticated model. Therefore, the previous kinematic results for West New Guinea have significant uncertainties, and the motion rates for the deformation area have not all been accurately estimated.

To address the issues mentioned above, we develop a broad-scale kinematic model that spans 5,000 km from longitude 110°E to 156°E, which in addition to microblocks in the western and eastern [IANGCZ](#) taken from the studies mentioned above, includes several new microplates in western New Guinea, as described below. For western New Guinea, the reprocessed data from 28 [GPS](#) sites allow us to

develop a completely new model that includes the Bird's Head Block and six new microplates in the central portion of the IANGCZ. These are the Yapen, Cendrawasih Bay, Tarera-Adiuna, Forearc, and West New Guinea Highland blocks, and the Mamberamo deformation zone (Yapen block (YAPE), Cendrawasih Bay block (CEND), Tarera-Adiuna fault zone block (TABL), Forearc block (FORE), West New Guinea Highland block (WNGH), and Mamberamo deformation zone (MDZ), respectively; Figure 4.3a). Also, some block boundaries defined in previous studies are adjusted to optimize the fit to the full dataset. Our new model links up the broader kinematic picture between PNG, Western New Guinea, and east Indonesia, which emphasizes first-order kinematic characteristics associated with deformation along the large-scale tectonic structures. We synthesize the previous regional GPS studies in conjunction with newly available geologic and seismologic observations from across the region to develop a consistent and coherent kinematic description for the whole IANGCZ.

4.3 Tectonic Setting and Kinematic Blocks

The east-west trending IANGCZ accommodates relative plate motion between the major tectonic plates through a complex system of fault-bounded tectonic blocks (Socquet et al., 2006; Stevens et al., 2002; Tregoning et al., 2000; Wallace et al., 2004). In this section, we consider the details of the tectonic setting along the IANGCZ, starting from eastern Java in the west and proceeding eastward to Papua New Guinea. We refer to Figure 4.1 for the locations of faults, deformation zones, fold-and-thrust belts, etc., and Figure 4.3 for the names of the blocks/microplates.

The western part of the IANGCZ has a tectonic setting that continuously transitions from subduction of Australian plate oceanic lithosphere south of Java to arc-continental collision in the Lesser Sunda Islands, in the western part of the Banda Arc. The Australian Plate has migrated northward rapidly since the Eocene, leading to the subduction beneath Java (Hall, 2011). This northward movement is also associated with the collision of the Australian continental lithosphere with the western

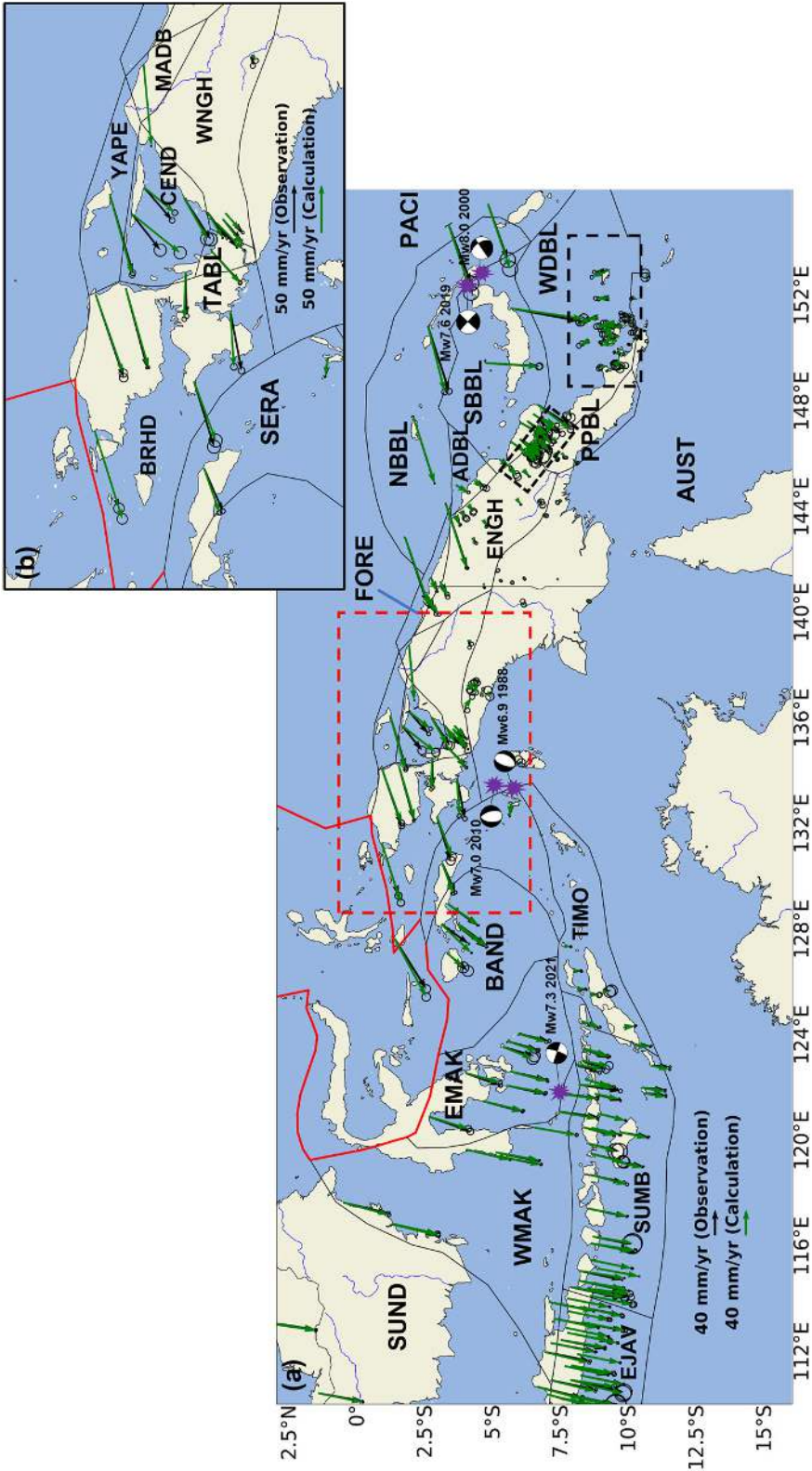


Figure 4.3: (a) Map showing our best-fit block model consisting of 23 plates/blocks. (Continued on next page.)

Figure 4.3: (Continued). Abbreviations are Sunda block (**SUND**), East Java block (**EJAV**), Sumba block (**SUMB**), West Makassar block (**WMAK**), East Makassar block (**EMAK**), Timor block (**TIMO**), Banda block (**BAND**), Seram block (**SERA**), Bird's Head block (**BRHD**), Yapen block (**YAPE**), Cendrawasih Bay block (**CEND**), Tarera-Adiuna fault zone block (**TABL**), Mamberamo deformation zone block (**MADB**), Forearc block (**FORE**), West New Guinea Highland block (**WNGH**), East New Guinea Highland block (**ENGH**), North Bismarck block (**NBBL**), South Bismarck block (**SBBL**), Adelbert block (**ADBL**), Papuan Peninsula block (**PPBL**), Woodlark block (**WDBL**), Australian Plate (**AUST**), and Pacific Plate (**PACI**). The focal mechanisms are derived from the Global Centroid Moment Tensor (**GCMT**). (b) The inset figure corresponds to the red dashed rectangle area in panel a, showing the close-up view of the observed and modeled global positioning system velocities in Western New Guinea. The zoomed-in view of the two black dashed rectangle areas (Ramu-Markham fault zone and Woodlark Rise) are shown in Figure B.4a and Figure B.4b of Supporting Information B, respectively.

Banda arc that began in the Pliocene (Hall, 2011; Roosmawati and Harris, 2009). This region marks a transition from Eurasian tectonic units in Java and Bali to Australian units in the Sumba and Savu Islands (Harris et al., 2009). Fold-and-thrust structures have been inferred from marine seismic surveys and the seismicity distribution, suggesting that back-arc thrusting occurs off the northern shores of Flores and Sumbawa Islands (McCaffrey and Nábelek, 1984; Silver et al., 1983). This back-arc thrust system, referred to as the Flores Back-arc Thrust (**FBT**), seems likely to have an important bearing on the evolution of the convergent margin.

GPS measurements of crustal deformation in this region demonstrate how the convergence between the Australian and Sunda Plate transitions from 95% accommodation at the subduction megathrust off eastern Java to 40% accommodation taking place along the **FBT**; this is in addition to strike-slip motion along the Semau Fault, stretching from the western tip of Timor to the island of Alor (Koulali et al., 2016; Nugroho et al., 2009). This variation in convergence style between eastern Java and the Banda Arc is associated with the lateral offset of continental collision and oceanic subduction (Miller et al., 2021). In one of the most recent **GPS** studies of eastern Indonesia, Koulali et al. (2016) divided the Sunda-Banda Arc into the three microblocks: East Java, Sumba, and Timor (**EJAV**, **SUMB**, and **TIMO**, respectively, in

Figure 4.3). Taking six new GPS velocities located in the Banda area into account, Cummins et al. (2020) revised the block geometry of Koulali et al. (2016) by using the active Banda detachment fault as a block boundary that separates the Banda block of Koulali et al. (2016) into the two microblocks, Banda and Seram (BAND and SERA in Figure 4.3a).

The Banda arc in the central part of the IANGCZ is well known for its near 180° bend within a tight 350 km radius of curvature. However, the formation of this spectacular curve has long been the subject of debate; there are two main hypotheses, the single-slab model and the two-slab model (Baldwin et al., 2012; Carter et al., 1976; Hamilton, 1979; Hinschberger et al., 2000, 2001; Spakman and Hall, 2010). According to the model of Chase (1978), based on intraslab seismicity, two plates are subducting beneath the Banda Sea. One subducts from the north at the Seram Trough, and the other subducts from the south at the Aru and Timor troughs. Where the Seram and Aru Troughs merge at the eastern end of the Banda Arc, they are separated by the sinistral Tarera–Aiduna Fault (Figure 4.1). These results were reinforced by later studies mainly based on fault plane solutions of earthquakes in Western New Guinea and the Banda arc (Abers and McCaffrey, 1988; Das, 2004). However, Spakman and Hall (2010) put forward a single-slab model which indicates that the spoon-shaped structure of the Banda slab is primarily caused by the rollback of dense oceanic lithosphere into an embayment enclosed by the continental crust of the Australian plate. This hypothesis also explains the lack of oceanic lithosphere, or signs of its consumption, between the Seram and Bird's Head blocks. It is further hypothesized that this slab rollback has driven lithospheric extension in the Banda Sea, much of which is accommodated by a massive normal fault known as the Banda Detachment on the western margin of the Weber Deep (Pownall et al., 2016).

East of the Banda Arc, the outline of the island of New Guinea is often described as having the shape of a bird, and it is divided geographically from west to east into the Bird's Head, Neck, Body, and Tail segments, as described in many studies

(e.g., [Cloos et al., 2005](#)). The Seram Trough, Sorong Fault, and Lengguru fold-and-thrust belt make up the Bird's Head region, which converges obliquely with Seram Island at the Seram Trough, driving a sinistral shear zone ([Bock et al., 2003](#); [Pubellier and Ego, 2002](#); [Stevens et al., 2002](#)). The Lengguru fault zone consists of internal and external zones, which have different tectonic regimes ([Bailly et al., 2009](#)). The internal zone is undergoing active extension which is believed to have started ~ 3 Ma, whilst the external zone is a compressional regime that accommodates the Australia-Pacific collision. The nature of this young extensional structure is still under debate ([Babault et al., 2018](#); [Bailly et al., 2009](#); [Charlton, 2000b](#)). The Tarera-Aiduna fault zone is the southern boundary of the Bird's Head and Neck regions, comprising a set of highly active east-west trending sinistral echelon faults ([Hamilton, 1979](#); [Katili, 1986](#); [McCaffrey, 1989](#); [Watkinson and Hall, 2017](#)). For most of its length, the Tarera-Aiduna Fault strikes almost parallel to the western end of the New Guinea Fold-Thrust Belt to the south, before it is terminated in an asymmetrical graben consisting of several NE–SW trending normal faults ([Watkinson and Hall, 2017](#)). Hence, the eastern Tarera-Aiduna Fault is highly seismically active with different stress regimes.

Cenderawasih Bay is a north-opening triangular embayment linking the Bird's Head block to the Central Ranges (Bird's Body) of mainland New Guinea ([Babault et al., 2018](#)). [Charlton \(2000b\)](#), and [Charlton \(2010\)](#) described the Cendrawasih Bay region as a triangular embayment formed by the $30\sim 40^\circ$ anticlockwise rotation of the Bird's Head block with respect to the Australian Plate since ~ 5 Mya, which suggests a rotation rate of $6\sim 8^\circ/\text{Myr}$. However, according to some stratigraphic and geomorphologic studies (e.g., [Babault et al., 2018](#); [Dow and Sukanto, 1984](#); [François et al., 2016b](#)), the geometry of Cenderawasih Bay has not changed significantly since the Neogene collision. [François et al. \(2016b\)](#) suggested that the Bird's Head block and the Lengguru Fold-and-Thrust Belt both belonged to the north Australian passive margin before the Neogene collision, and their southwestward drift in the late Miocene resulted in the formation of Cenderawasih Bay, a hypothesis that was sup-

ported by Babault et al. (2018) by combining drainage network analysis, interpretation of seismic lines and thermochronological data assessment.

The GPS measurements from 1991 to 1997 show 75.0 to 80.0 mm/yr southwest motion of BRHD, Figure 4.3) relative to Australia along a wide shear zone (Stevens et al., 2002). This result is consistent with the study of Pubellier and Ego (2002), which suggested that the BRHD of West New Papua is an example of escape tectonics, resulting from the collision between the remnants of volcanic belts carried by the Pacific Plate and the Australian Plate with the rate reaching 70.0 mm/yr based on seismicity, micro-tectonic data, and synthetic aperture radar. Bock et al. (2003) generated a relatively simple kinematic model for Western New Guinea, which regarded the Bird's Head region and Cenderawasih Bay as a single block. They computed the Euler pole of rotation for the Bird's Head block, suggesting that it rotated anticlockwise at the rate of $2.92 \pm 0.45^\circ/\text{Myr}$ with respect to the Australian Plate.

There are two active inland deformation areas in the Bird's Body section, the Memberamo deformation zone and the NGFTB. The Memberamo region is characterized by fields of active mud volcanoes and an irregular swampy landscape. It has been regarded as a broad compressive arc that connects the Yapen and Bewani-Torricelli sinistral strike-slip fault zones (Sapiie et al., 1999; Williams et al., 1984). Further west, the Yapen fault links with the Sorong fault zone (Baldwin et al., 2012).

The NGFTB is a 4-km-high, 1,300-km-long, E-W trending mountain belt, which stretches from the Bird's Neck (at the eastern Tarera-Aiduna Fault) to its Tail (west of the Papuan Peninsula) (Abers and McCaffrey, 1988; Baldwin et al., 2012; Bock et al., 2003; Cloos et al., 2005). Convergence resulting from the oblique collision between the Australian Plate and the Pacific Plate is partially accommodated by sinistral motion on the Tarera-Aiduna Fault in western New Guinea and reactivation of the thrust front of the NGFTB (Abers and McCaffrey, 1988; Dow and Sukanto, 1984; Puntodewo et al., 1994). The convergence rate between the Australian and Pacific plates is around 110 mm/yr, and only 5–20% of the convergence is accommodated

by the [NGFTB](#) based on the volume of the uplifted mountain range and present-day earthquake activity ([Abers and McCaffrey, 1988](#); [Bock et al., 2003](#)). The other candidates for the accommodation of the remaining convergence are the New Guinea Trench inside the Bird's Body section, and a complicated array of microplates with a variety of plate boundary types in the Bird's Tail region, including a strike-slip transform system (Bismarck Sea Seismic Lineation [[BSSL](#); [Taylor, 1979](#)], collision orogenesis ([Abers and McCaffrey, 1988, 1994](#); Finisterre Arc; [Silver et al., 1991](#)), a rifting system (Woodlark; [Taylor et al., 1991](#)) and subduction zones (New Britain Trench; [Silver et al., 1991](#)).

The active Bismarck Sea Seismic Lineation ([BSSL](#)) is a zone of spreading segments and sinistral transform faults which separates the Bismarck Sea into South Bismarck ([SBBL](#)) and North Bismarck ([NBBL](#)) blocks ([Taylor et al., 1991](#); [Tregoning et al., 1999](#)). The subduction of the Solomon Sea forms the New Britain Trench ([NBT](#)), which also drives the seafloor spreading and rifting in the Woodlark Basin and Woodlark Rift ([WR](#)), respectively ([Weissel et al., 1982](#)). The style of the plate boundary between the Australian and Woodlark plate accommodates a transition from divergence (the Woodlark Rift) to convergence (the Papuan Peninsula) over 500 km, along a reactivated megathrust known as the Owen-Stanley fault zone, which connects with the Ramu-Markham fault that is formed due to the collision between the New Guinea Highland Block and the South Bismarck Sea ([SBS](#)) block ([Davies and Smith, 1971](#); [Ott and Mann, 2015](#); [Wallace et al., 2004](#)).

In [PNG](#), the first tectonic block model was developed by ([Tregoning et al., 1998a](#)), which divided the [PNG](#) area into South Bismarck and Woodlark blocks ([SBBL](#) and [WDBL](#), Figure 4.3a). [Tregoning \(2002\)](#) added a new block (North Bismarck block denoted [NBBL](#) in Figure 4.3a) into their [PNG](#) model. The Eastern New Guinea Highland, Adelbert, and Papuan Peninsula blocks ([ENGH](#), [ADBL](#), and [PPBL](#)) were proposed and analyzed by [Wallace et al. \(2004, 2014\)](#). [Wallace et al. \(2004\)](#) used [GPS](#) data in the New Guinea Highlands to show the [ENGH](#) has motion distinct from the

Australian Plate, and similarly proposed the existence of a separate [ADBL](#). They simultaneously estimated block Euler vectors in eastern New Guinea and interseismic fault locking on the Ramu Markham Fault using a densified network of sites through the New Guinea Highlands and Finisterre collision zone, adding 35 new sites to the previously sparse network in the region. In contrast, the model of [Koulali et al. \(2015\)](#) included additional data from the New Guinea Highlands region and found that the [ENGH](#) rotates clockwise about a pole located northwest of the block. [Wallace et al. \(2014\)](#) made geodetic measurements at a dense network of sites in the Woodlark Basin/Papuan Peninsula region in southeast Papua New Guinea, to undertake a detailed assessment of the distribution and rates of rifting in the [WR](#), defining several microblocks along the [WR](#).

4.4 Data and Method

4.4.1 GPS Velocities and Earthquake Slip Vectors

We reprocessed [GPS](#) observations collected from 28 campaign stations located in West New Guinea and acquired two new [GPS](#) data from the stations at Timor Island ([McCaffrey, 2002, 2005](#)). The reprocessed data were collected from 2002 to 2004 and processed using the [GAMIT/ GLOBK](#) software suite ([Herring et al., 2015a,b](#)). The [GPS](#) sites were observed with three different antenna and receiver combinations: TRM29659.00/Trimble 4000 SSI, TRM41249.00/Trimble 5700, and ASH701975.01A-GP/Ashtech UZ-12.

In East Timor, new [GPS](#) observations from the stations DILI and SAME were processed. The DILI station is a semi-permanent station occupied from 2018 to 2019. The SAME station is a campaign station that has been surveyed in 2005, 2018, and 2019. Both stations were occupied using TRM39105.00/Trimble 5700. The [GPS](#) data processing procedure follows the two-step approach described by [Reilinger et al. \(2006\)](#). In the first stage, we used [GAMIT](#) to obtain the ‘h-files’, a loosely constrained covari-

ance matrix of station positions. Using [GAMIT](#), the ionosphere-free combination of phase observations was used to estimate station positions, phase ambiguities, earth rotation parameters, and the zenith troposphere delay while the [IGS](#) final satellite orbits were held fixed. The [IERS2010](#) standard solid Earth tide and sub-daily earth rotation correction models and the [FES2004](#) ocean tide loading model corrections computed by the Onsala Space Observatory were applied. In the second stage, we used the [GLOBK](#) to combine data in a single solution and generate velocity field estimates and position time-series. We include the [GPS](#) data from 13 continuous [IGS](#) global stations to tie our local network into the [ITRF 2014](#) reference frame. We also used the first-order Gauss–Markov extrapolation algorithm described in [Herring et al. \(2015b\)](#) to estimate the realistic noise properties of the [GPS](#) time-series used to scale the estimates of velocity uncertainties. This procedure has been used previously and reviewed extensively in many studies (e.g., [Koulali et al., 2015, 2016, 2017](#); [Reilinger et al., 2006](#); [Wallace et al., 2004, 2014](#)). The position time-series are examined for offsets and outliers, resulting from antenna changes or earthquakes ([Tregoning et al., 2013](#)). However, the [GPS](#) sites at Western New Guinea are not temporally dense enough to enable correcting of the coseismic offsets. Therefore, we excluded the nine [GPS](#) velocities which were displaced coseismically by a series of earthquakes with $M_w \geq 5.5$ that occurred at the southern Lowland faults and northern Lengguru fault, between 2002 and 2004 in Western New Guinea (Figure [B.1](#) of Supporting Information [B](#)).

We combined the velocity estimates from the 28 reprocessed and two newly processed stations with the velocities published in previous studies, including [Biemiller et al. \(2020\)](#); [Bock et al. \(2003\)](#); [Cummins et al. \(2020\)](#); [Genrich et al. \(1996\)](#); [Koulali et al. \(2015, 2016, 2017\)](#); [Kreemer et al. \(2014\)](#); [Meilano et al. \(2021\)](#); [Phillips \(2003\)](#); [Tregoning et al. \(1998a\)](#); [Tregoning et al. \(1998b\)](#); [Tregoning et al. \(1999\)](#); [Stevens et al. \(2002\)](#); [Simons et al. \(2007\)](#); [Wallace et al. \(2004, 2014\)](#). Since this study combined data from several different solutions and studies, there are often multiple ve-

locity estimates available for sites; in this case, we computed the weighted average of the velocity estimates which are within two standard deviations, and we also considered the uncertainty of the estimates from different studies. After removing duplicates and outliers as described above, 267 high-quality GPS velocities were selected for inversion. Finally, in order to better analyze the kinematic pattern of the entire broad-scale model, we choose the Australia Plate which interacts with the entire length of the IANGCZ as the reference frame. All the velocity solutions were optimally rotated into the Australia-fixed reference frame by resolving a rotation of the dataset that minimizes the velocities at the sites located in the Australia Plate using TDEFNODE (McCaffrey, 2009), which applies simulated annealing to downhill simplex minimization (Press et al., 1989). The 267 GPS velocities are presented and plotted in an Australian-fixed reference frame in Table B.1 of Supporting Information B, Dataset of Supporting Information B, Figure 4.2, and Figure B.2 of Supporting Information B.

Earthquake slip vectors are derived from earthquake focal mechanisms, which provide important information about the directions of plate motion in estimating the Eulerian pole of each block/plate (Aki and Richards, 1980; DeMets et al., 1990, 1994). For the kinematic modeling, earthquake slip vectors can be used to constrain the azimuth of block motions (Koulali et al., 2015, 2016; Wallace et al., 2004; Tregoning and McQueen, 2001). In our study, we utilized 492 earthquake slip vector azimuths in total (Figure B.3 of Supporting Information B; Dataset B.5 of Supporting Information B). Most of them are derived from the Global Centroid Moment Tensor (GCMT; Ekström et al., 2012) catalog for events shallower than 100 km and $M_w > 5.5$ from 1976 to 2018. We also include the earthquake slip vectors used in Koulali et al. (2015). We allowed 20° uncertainties in slip orientation in the inversion. Since for any moment tensor, there are two nodal planes, either of which may correspond to the actual fault plane, each calculated earthquake slip vector can have one of two possible azimuths (Cronin, 2004). Hence, we made geologically reasonable choices

for the slip vectors, by considering the detailed tectonic maps and mapped faults (Figure 4.1).

4.4.2 Kinematic Modeling

Observed long-term crustal velocities can be modeled as a sum of high rates of internal strain accumulation in the areas adjacent to block boundaries and rigid block rotations specified by Euler pole rotations (McCaffrey et al., 2000, 2002; Meade and Hager, 2005). We follow the block modeling method in TDEFNODE (McCaffrey, 2009), which specifies the block motions via angular velocities on the surface of a sphere and applies interseismic “back-slip” along the block boundaries (Savage and Burford, 1973). All the GPS velocities and earthquake slip vectors are inverted simultaneously to estimate the Euler vectors of blocks and coupling fractions, defined as the ratio of locked to total slip on the major block boundary faults. Block boundaries are the most important prerequisites for the inversion, and they were initially determined from the seismicity ($M_w \geq 5$) distribution (Figure 4.2), GPS velocity field (Figure 4.2), mapped faults (Figure 4.1), and the models from previous studies (e.g., Bock et al., 2003; Cummins et al., 2020; Koulali et al., 2015, 2016; Stevens et al., 2002; Wallace et al., 2004, 2014). The choice of threshold magnitude for earthquake data varies among the previous kinematic studies, which choose a similar or even smaller magnitude threshold than used here for the initial boundary determination (Koulali et al., 2015, 2016; Reilinger et al., 2006; Wallace et al., 2004, 2014). The block boundaries were then adjusted by minimizing the data misfit as expressed by the chi-square statistic χ_n^2 value and applying the ratio F-test to verify the significance of fit improvement (Stein and Gordon, 1984).

In Western New Guinea, the downdip geometry for the subduction zone is based on the U.S Geological Survey’s Slab 2.0 model (Hayes et al., 2018), and seismicity cross-sections for the other block boundary faults not covered by Slab 2.0 (e.g., Leng-guru fault zone, Lowlands fault zone, Ransiki fault zone, and Mamberamo deforma-

tion zone). Fault nodes are placed along the depth contours of the faults, every 5 km in the upper 30 km and every 10 km from 30 to 50 km. We considered as free-slip (i.e., locking is constrained to zero) boundaries those block boundaries that are less well determined due to: the lack of historical earthquakes; no coverage by the Slab 2.0 model; lack of good GPS coverage and/or ambiguity in the tectonic maps (Figure 4.1). As described above, in the Sunda-Banda region and PNG, most boundary faults and block geometries are mainly described based on Koulali et al. (2015, 2016), respectively. Compared to Koulali et al. (2015), Wallace et al. (2014) have given the Woodlark region, southeast PNG, a more detailed kinematic analysis, including additional microblocks. Considering that the main aim of our study is to investigate the large-scale first-order tectonic structures, our southeast PNG block geometries were derived from the simpler model in Koulali et al. (2015), rather than attempting to reproduce the work in Wallace et al. (2014). However, some geometries of the blocks located in the central IANGCZ (e.g., FORE and ENGH blocks) are revised in this study according to recently mapped faults, updated GPS velocity field, and relocated seismicity distribution so that the merged broad-scale block model is tectonically and geodetically reasonable. The updated GPS velocities give us more comprehensive observations of the deformation, which allows us to improve the block model constraints. We parameterize the locking along the Sunda-Banda forearc and Flores back-arc thrust as a modified (Wang et al., 2003) function such that the full coupling ratio ($\Phi = 1$) decreases down-dip exponentially until no coupling ($\Phi = 0$). The depth of the top and bottom of the transition zone are parameters determined by the inversion. The locking parameters for the active boundaries of PPBL, SBBL, NBBL, and WDBL are derived from the previous PNG kinematic model in Koulali et al. (2015). The parameterization of the other boundary faults in our model is simplified by fixing uniform locking to the depth of 10~20 km, in order to reduce the number of free parameters.

4.5 Preferred Best-Fit Model Geometries

Our best-fit kinematic model consists of 23 crustal blocks (Figure 4.3) and was compared with 10 models having different geometrical configurations (Figure B.5 and Table B.3 of Supporting Information B). We compare the values of Normalized Root Mean Square (NRMS) and Weight Root Mean Squared (WRMS) of the corresponding blocks in the different models, which provides a statistical measurement of the variance between the predicted values and observed GPS velocity values on common blocks (Barondess and Utku, 1963; Chen et al., 2010; Di Piazza et al., 2016; Willmott and Matsuura, 2006). The F-ratio test put forward by Stein and Gordon (1984) is also performed in this study to verify the significance of changes in the fit between competing models (Table B.3 of Supporting Information B). The best-fit model suggests a higher goodness-of-fit for the earthquake slip vectors in the eastern PNG area (Figure B.3 of Supporting Information B). This is consistent with the deformation in the Bismarck Sea seismic lineation and NBT in eastern PNG being predominantly controlled by the high-slip first-order tectonic structures. Whereas some deformation zones in the Banda arc and West New Guinea regions (e.g., Lowlands and Lengguru fault zones) comprise a series of small-scale faults with similar regimes, which leads to the relatively high residuals, as our model simplifies these deformation zones as single large-scale tectonic boundaries.

In Western New Guinea, we suggest a new model geometry that subdivides the region into eight micro-blocks. Unlike previous studies (e.g., Bock et al., 2003; Stevens et al., 2002), which defined the Bird's Head and Neck regions as a single block, we consider the Bird's Head and Neck regions as separate blocks. We split the Cenderawasih Bay area into three micro-blocks (YAPE, CEND, and TABL) using the Biak Thrust, Yapen Fault, Weyland Overthrust, Lowlands fault zone, Lengguru fold-and-thrust belt, and Tarera-Adiuna Fault as the active block boundaries. The highly seismically active MDZ connects sinistral strike-slip motion on the Yapen Fault in the west with the same style motion on the Bewani-Torricelli fault in the east (Cloos et al.,

2005; Sapiie et al., 1999). Together these are considered as the southern boundary of the FORE block in our study. According to the distribution of the historic earthquakes in this area (Figure 4.2), the southeast tip of the MDZ connects with the sinistral Tahin fault zone (Figure 4.1), which separates the Bird's Body region into WNGH and ENGH blocks (Figure 4.3). Although the seismological data illustrates that the WNGH and CEND blocks could be subdivided into more complex configurations, additional microblocks will not improve the goodness of fit statistically due to the low density of GPS observations (Figure 4.3).

For the Sunda-Banda area, we applied similar block geometries to Koulali et al. (2016). However, since new GPS observations from the Banda region were used in the inversion, the previous kinematic model configurations from Koulali et al. (2016) illustrated distinct residuals, especially for site CUAL, which revealed that the Tual Island site should not be modeled in the TIMO block (Figure B.5b of Supporting Information B). Cummins et al. (2020) put Tual Island (site CUAL) and Yamdena Island (site CSAU) into the same SERA block, obtaining a relatively small residual at each site, whilst the SERA block exhibited large NRMS/WRMS and χ_n^2 values (9.14/2.69 and 11.1, respectively), (Figure B.5c of Supporting Information B). We found that these NRMS/WRMS and χ_n^2 values for the SERA block can significantly decrease to 2.71/0.75 and 9.4 when the site CSAU is instead included in the TIMO block, while for the TIMO block, the statistic measurements did not show a demonstrable change. This indicates that the tectonic block in which site CSAU is located has the same kinematic properties as the sites in the TIMO block. Hence, we modeled the SERA block as one curved block, including the entire Weber deep and bounded in the east by the Aru and Seram Troughs, and bounded in the west by the Banda Detachment and Kawa Shear Zone, which cuts through the length of Seram Island. We merge Yamdena Island into the TIMO block, utilizing the Timor Trough and Tanimbar Trough as the southern boundary of the TIMO block. We utilized a boundary based on seismicity separating the TIMO and SERA blocks to decrease the χ_n^2 value and satisfy

an F-test (Figure B.5 and Table B.3 of Supporting Information B). This new boundary setting is consistent with the seismic zone defined by Rahmadani et al. (2022).

Koulali et al. (2016) defined the boundary between the Western and Eastern Makassar Blocks (WMAK and EMAK, respectively) by combining the southern Palu, Masupu, and Walanae Faults, extending the latter offshore along the Selayar Trough, and then continuing this boundary in a southward direction until it connects with the Flores Back-arc Thrust. We note, however, that this latter southward extension is not well supported by bathymetry or seismicity, and does not follow the Selayar Islands chain where it bends sharply eastward, just south of the Selayar Trough. In December 2021 a large, M_w 7.3 earthquake occurred with a dextral rupture along a fault oriented along this southeast extension of the Selayar Islands chain (GCMT). We have therefore adjusted the EMAK/EMAK boundary to follow this eastward bend in the Selayar island chain, extending southeastward along the strike of the 2021 earthquake until it connects with the Flores back-arc thrust (Figure 4.2; Figure 4.3a). This coincides with the Kalaotoa Fault identified by Supendi et al. (2022) as the source of the 2021 earthquake.

4.6 Some Implications Based on the Broad-Scale Kinematic Model Results

The relative slip rates across the block boundaries between the adjacent blocks and the Euler rotation rate of each block derived from our best-fit model are shown in Figure 4.3 and Table B.2 of Supporting Information B, respectively. We compared our estimated Euler vectors with the results from previous studies, as summarized in Table B.2 of Supporting Information B. To understand the slip partitioning mechanism, we also decompose slip rates into normal and parallel components (Figure 4.5).

Most of our results show some agreement with previous estimates, and our more comprehensive datasets give better constraints and smaller uncertainties. On the

other hand, there are many areas that still lack enough GPS measurements to provide well-constrained block velocities, in which case the uncertainties are considerable. The Yapen fault zone (YFZ), as expressed in the Biak Basin, actually consists of two parallel, active sinistral faults striking WNW-ESE and separated by a 30 km zone of complex faulting (Memmo et al., 2013). The GPS sites on Yapen Island (POM2 and YAPE) are affected by this complex internal deformation on the island, causing the relatively large modeling residuals at these two sites. In addition, according to the earthquake distribution (Figure 4.2) and focal mechanisms (Figure 4.6), a dextral strike-slip fault extends from Yapen Island to the Lowlands fault zone, forming an active strike-slip deformation zone at the northeast corner in our CEND block, which drives the slip at the north Lowlands fault zone but is not involved in the block modeling since there are no GPS observations to constrain this unmapped strike-slip fault (Figure 4.3). Hence, we exclude from our analysis the GPS site WREN located near this possible active boundary, to avoid having NW-SE motion on this fault influence the block modeling (Figure 4.2; Figure 4.6). In our model, the Yapen fault and Tarera-Adiuna fault are highly active with 36.9 ± 3.9 and 61.3 ± 1.4 mm/yr predominantly sinistral slip, respectively, consistent with the existence of local extensional structures (Charlton, 2000b, 2010; Cloos et al., 2005). Our estimated relative motion rate along the Tarera-Adiuna fault is consistent with the early seismic study of McCaffrey and Abers (1991), which suggested the Tarera-Adiuna fault zone accommodates ~ 60 mm/yr of sinistral motion.

4.6.1 Kinematics for Three Triple Junction Systems in the Model

Along the eastern boundary of the SERA block, the kinematic scenario shows a transition from thrusting to normal faulting, marked by its intersection with the highly active sinistral Tarera-Adiuna Fault which separates the Seram from the Aru Trough. The Banda block shares the same boundary as the SERA block, indicating 23.8 ± 1.2 mm/yr of sinistral slip rate along the Kawa Shear Zone. This sinistral slip continues

along the Banda Detachment with a small component of normal slip (~ 12 mm/yr). The Bird's Head Block rotates anticlockwise relative to the Australian Plate at a rate of $2.82 \pm 0.11^\circ/\text{Myr}$, resulting in an average 26.7 ± 1.3 mm/yr of southwestward motion that is accommodated by the Tarera-Adiuna fault to the south, and contributes to convergence along the Seram Trough (Figure 4.4; Figure 4.5). The Tarera-Adiuna Fault intersects the outer Banda Arc where the Seram and Aru Troughs meet, accommodating a shift in footwall movement from SW (i.e., convergent) to NE (i.e., divergent) motion relative to the Australian plate with an average rate of ~ 25.1 mm/yr. This extensional movement is consistent with the recorded focal mechanisms (Figure 4.3) and also provides kinematic evidence for the Spakman and Hall (2010) rollback model in the Banda arc, explaining the formation of this spoon-shaped embayment. The SERA, BRHD, and AUST blocks comprise a triple junction system. The three boundaries consist of a compressional Seram Trench, an extensional Aru Trough, and a sinistral strike-slip Tarera-Adiuna Fault, following the Ridge–Trench–transform Fault type put forward by McKenzie and Morgan (1969) and showing high stability based on the estimated relative velocity vectors (Kearey et al., 2009).

In the PNG area, comparing with Koulali et al. (2015), in addition to the GPS data derived from Koulali et al. (2015), we added the GPS velocities from Wallace et al. (2014) and Biemiller et al. (2020) into the inversion. These additional velocities are mainly distributed around the Huon Peninsula, Papuan Peninsula, and D'Entrecasteaux Islands. Although some of the tectonic complexity of this region results in internal block deformation not associated with block boundary locking, our model provides a good fit for the GPS observations in Southeastern PNG. This suggests that most of the deformation is associated with the rotation and locked boundaries of the blocks in our model. Also, our results for block boundary slip are mostly consistent with previous studies on the crustal block rotation and strain associated with fault locking (Biemiller et al., 2020; Wallace et al., 2014). For example, the rapid clockwise rotation of the south Bismarck plate results in a rapid

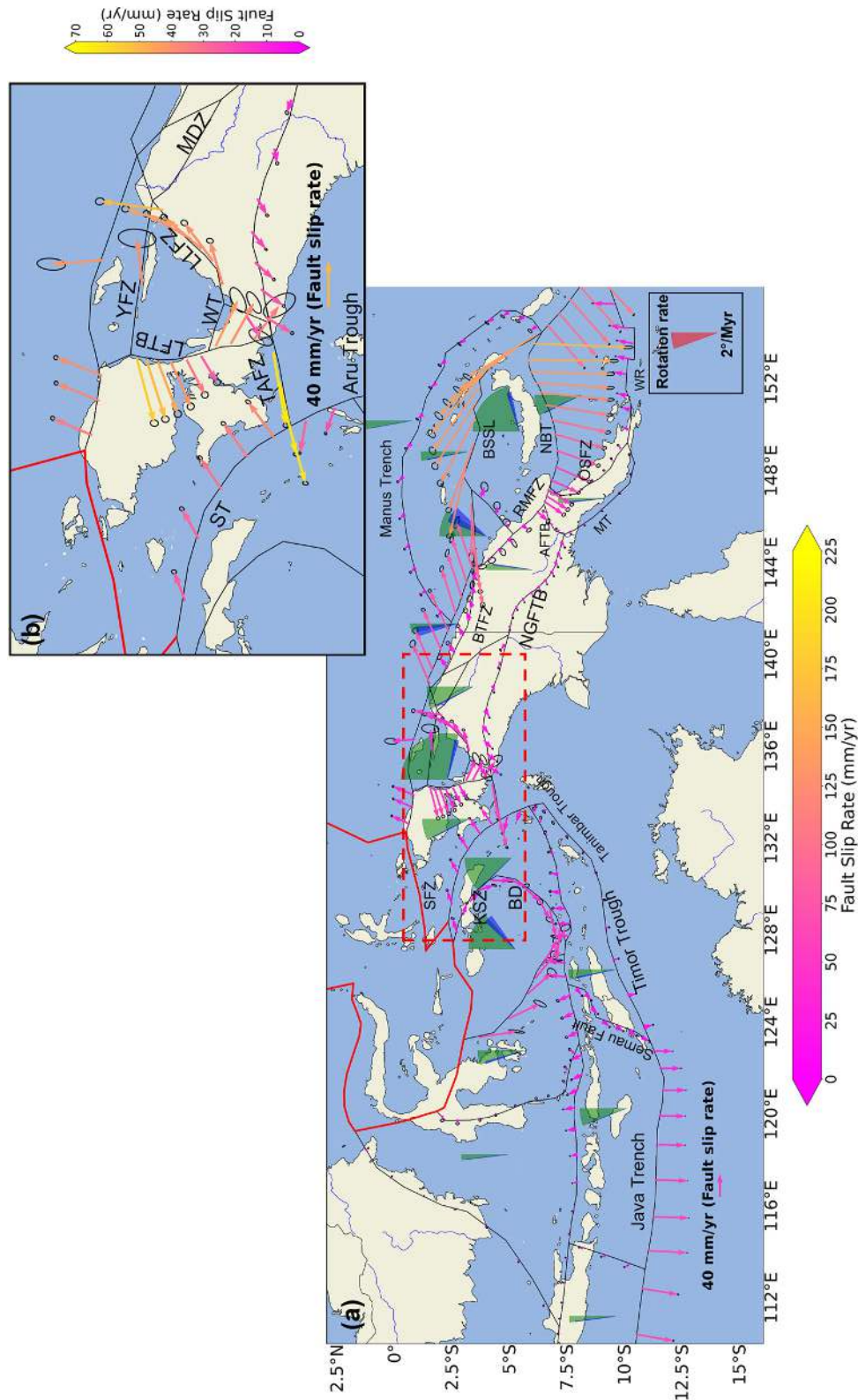


Figure 4.4: (a) Relative fault slip vectors across the active block boundaries with 95% error ellipses. (Continued on next page.)

Figure 4.4: (Continued). The abbreviation of each active fault has been defined and indicated in Figure 4.1. The magnitude of the slip vectors is proportional to the size of the arrows. Arrows show the movement of a hanging wall relative to a footwall, and the tails of arrows are located on the hanging wall. The green wedges represent the block rotation rate with respect to the Australian Plate. If the wedge is open to the west, it represents the anticlockwise rotation of the block, or conversely (scale is located at the lower right corner in red). The blue wedges indicate the uncertainties of the rotation rates. Since the [YAPE](#), [TABL](#), and [MADB](#) blocks only contain one [GPS](#) observation, the rotation estimates have significant uncertainties. Therefore the results are not shown here. For the northern boundary of the Yapen fault, we chose to use the estimated slip vector with the smallest uncertainty located both near the [GPS](#) velocity in the Yapen block and related earthquake slip vectors to indicate the deformation of the Yapen fault northern boundary. The estimated location of the Euler pole for each block is given in Table B.2 of Supporting Information B. (b) The inset figure corresponds to the red dashed rectangle area in panel a, showing the close-up view of the estimated slip vectors in Western New Guinea. Note that the color scale is different for each figure.

escalation of convergence rate along the Ramu-Markham fault: from 3.4 ± 0.3 mm/yr at the northern end of the west [ADBL](#) boundary to 25.2 ± 1.7 mm/yr at the Huon Peninsula area, and it increases further to 45.5 ± 1.5 mm/yr at the junction of the [NBT](#) and Ramu-Markham fault, which is consistent with [Wallace et al. \(2004\)](#) (Figure 4.3 and Figure 4.4). The convergence rate also increases along the New Britain Trench, reaching 149.6 ± 3.3 mm/yr at 152.8°E , which is consistent with [Wallace et al. \(2014\)](#) indicating the highest convergence on the [NBT](#) is up to ~ 150 mm/yr. The estimation of the pole of rotation of the Woodlark block with respect to the Australian Plate is at longitude 147.82°E , latitude -9.19°S with an anticlockwise rotation of $2.61 \pm 0.06^\circ/\text{Myr}$, resulting in decreasing extensional rates from 43.4 ± 0.9 mm/yr at 156.8°E to 10.4 ± 0.3 mm/yr at 149.8°E along the Woodlark Rift, with continued reduction in slip rate along the Owen Stanley fault zone to as low as ~ 1 mm/yr. Again, these are close to the estimated slip rates along the same faults in [Wallace et al. \(2014\)](#) using the Trobriand Block/Australian Plate Euler pole rotation. [Wallace et al. \(2014\)](#) studied the Woodlark area in more detail, subdividing the [WDBL](#) of this paper into six smaller microblocks, including a Trobriand Block and the Solomon Sea and Woodlark Plates. While this finer microblock configuration reveals impor-

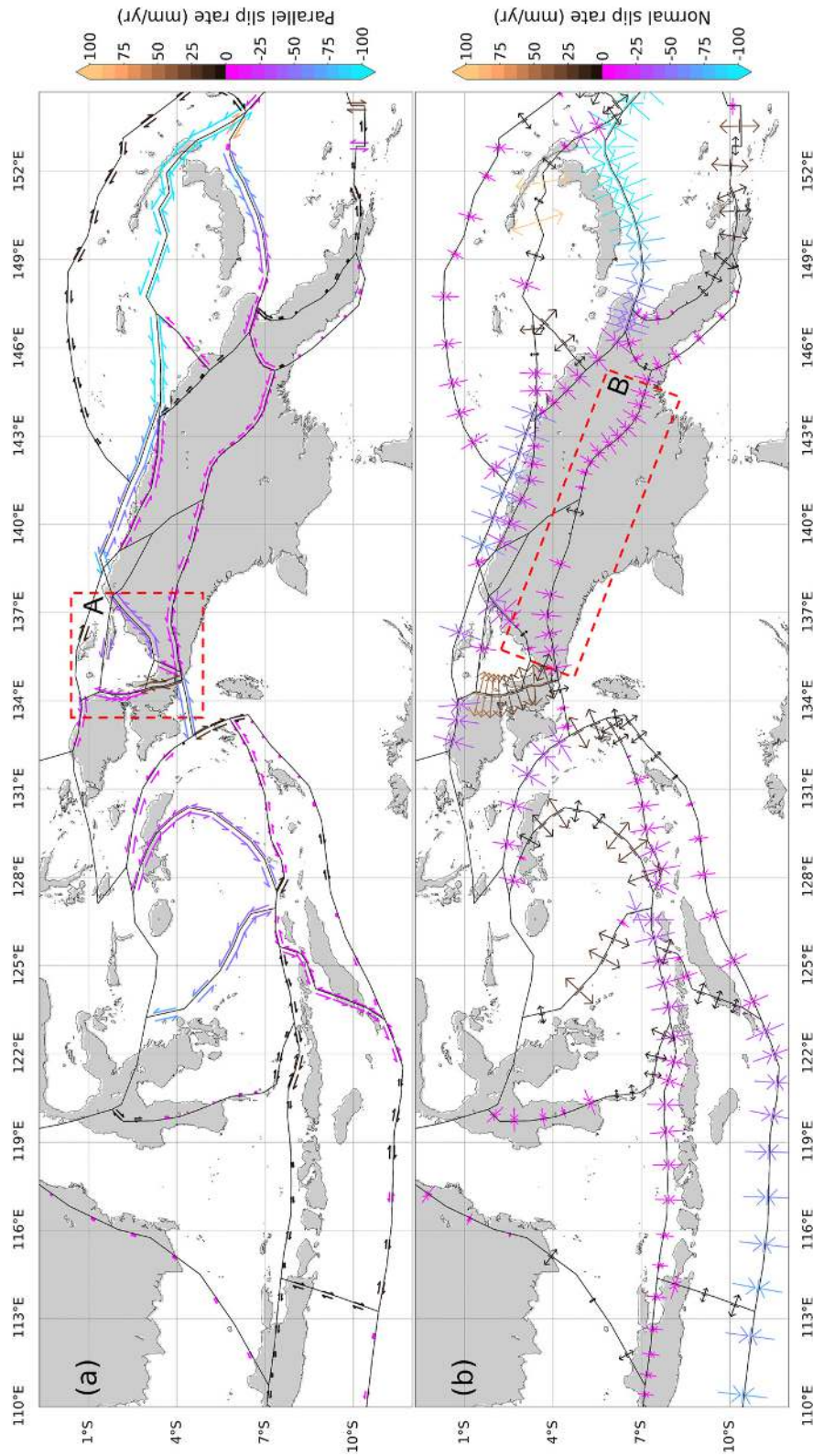


Figure 4.5: (a) The fault-parallel component of relative fault slip rates; positive value represents dextral strike-slip, and a negative value represents sinistral strike-slip. (Continued on next page.)

Figure 4.5: (Continued). (b) The fault-normal component of relative fault slip rate; positive value represents an extension, and a negative value represents compression. The value of the slip rate is logarithmically proportional to the size of the symbol for better visualization. The dashed rectangles A and B represent the area that will be further discussed in Figures 4.6 and 4.7, respectively.

tant details of the extension and continental breakup occurring in this part of PNG, our results for the larger-scale block movement and fault slip are very similar to those of Wallace et al. (2014). For example, the Trobriand block in Wallace et al. (2014) is the largest of the six microblocks, accounting for over 60% of our WDBL, and the estimated pole of rotation of our WDBL is consistent with that of Wallace et al.'s (2014) Trobriand block, $-2.69 \pm 0.13^\circ/\text{Myr}$ with the pole at the longitude 147.85°E , latitude -9.54° (Table B.2 of Supporting Information B).

The pre-rift evolution of the Woodlark Basin includes arc volcanism, subduction, and arc-continent collision, which was partially accommodated by the Moresby Trough (MT; Baldwin et al., 2012). As the southwest boundary of the PPBL Block, we estimate a convergence on the order of 4 mm/yr across the MT. While the Aure Fold-and-Thrust Belt (AFTB) is a region of diffuse seismicity likely reflecting activity on the distribution of small faults, we have represented it as a single fault that separates the Eastern Highlands and the Papuan Peninsula blocks (ENGH and PPBL, respectively). Our estimate for relative motion on the AFTB increases from 5.7 ± 0.9 at its southern end, where it merges with the Moresby Trough (MT), to 6.5 ± 0.6 mm/yr at its northern end, where it intersects the Ramu-Markham fault zone (RMFZ).

We note our kinematic model results in extremely high relative velocity along the Weitin Fault, at the boundary between the North and South Bismark blocks (NBBL and SBBL, Figures 4.1 and 4.3a). Previous studies have also resulted in high slip rates along this transform fault zone, with Tregoning et al. (1999) obtaining 130 mm/yr, Wallace et al. (2004) 140 mm/yr, and Koulali et al. (2015) 144 mm/yr. The sinistral relative block motion we obtain is 145.7 ± 3.1 mm/yr but could be higher (up to ~ 171 mm/yr) if include site RABL in the analysis (Tregoning et al., 1998a, Figure B.1 of

Supporting Information B). The site RABL was not included in our analysis because it is on a highly active volcano and its velocity may be strongly influenced by volcanic processes unrelated to plate motion. However, the influence of the volcano activity on site RABL has not been quantified, so we cannot exclude the possibility that it is small, and that the velocity of RABL is reflecting an even higher slip rate along the Weitin Fault of 171 mm/yr.

This compares with 50–57 mm/yr along the Queen Charlotte Fault offshore western British Columbia, described by (Brothers et al., 2020) as having “the fastest rate for a continent-ocean strike-slip fault on Earth”, or 42 mm/year for the Palu Koro Fault in Indonesia (Socquet et al., 2006), which is also regarded as having a very high slip rate. While some ocean transform faults, such as some relatively short transform segments along the East Pacific Rise (Lonsdale, 1978) or near the northern edge of the Tonga Trench, may have higher slip rates, we believe the Weitin fault has by far the highest slip rate of any major (i.e., greater than 200 km length) transform fault on earth. This is possible even if we allow that accommodation of the relative block motion may be shared with other small-scale parallel faults in New Ireland (Lindley et al., 2006). The Weitin fault experienced an overlapping rupture in two recent major earthquakes in 2000 and 2019 (M_w 8.0 and 7.7, respectively), and Ghasemi et al. (2020) have shown that high seismicity is commensurate with a very high slip rate.

4.6.2 Deformation Rates on the Sunda-Banda Subduction System

From the Java Trench to the Timor Trough, the estimated relative slip rates show an eastward decreasing trend, from 65.1 ± 0.3 mm/yr (at 112.4°E) to 10.9 ± 0.3 mm/yr (at 126.7°E). The direction of the slip rates across this boundary shows a sudden change from southward to southeastward, a transition which is accommodated by and coincides with the intersection with extensional/sinistral motion on the Semau Fault (Figure 4.4). This progressive change in the relative velocity and slip azimuth is also apparent in the back-arc region, where it has the opposite sense to the change

in motion on the megathrust. The slip rate on the Flores back-arc thrust gradually increases eastward from 4.8 ± 0.5 mm/yr at 110.4°E to 29.9 ± 2.0 mm/yr at 126.5°E , with the change again dictated by its intersection with the Semaui Fault (Figure 4.4). Furthermore, in the east, the relative velocity along the back-arc changes to a more eastward direction, indicating a shear component of motion, which is consistent with the earthquake focal mechanisms as shown in Figure B.3b of Supporting Information B. The relative slip rates we obtained along the Sunda-Banda megathrust and Flores back-arc thrust are slightly smaller than those estimated in Koulali et al. (2016), mainly because of the GPS velocities we newly applied on Java and Timor Island, which have slightly slower velocities, and the revised block boundaries for SUND, EMAK, and WMAK blocks. In the TIMO block, our two new GPS observations (stations DILI and SAME) first reveal the deformation in East Timor and better constrain the deformation rate on the boundary of the block. Compared with the motion of the TIMO block suggested by Koulali et al. (2016), our block scenario decreases the NRMS/WRMS value significantly, from 4.05/2.14 to 2.48/1.34.

4.6.3 Geodetic Implications for the Tectonic Evolution of Cenderawasih Bay

As mentioned above, the origin of Cenderawasih Bay is the subject of ongoing debate. Our kinematic model provides some geodetic constraints for the development of Cenderawasih Bay by quantifying the movement on the active block boundaries. The decomposition of relative block motion depicted in Figure 4.5 highlights the opposing tectonic regimes on the west and east boundaries (Lengguru and Lowlands fault zones) of CEND (Figure 4.5). The relative movement along the west boundary shows significant partitioning of extensional deformation decreasing southward, from 50.3 ± 1.8 to 25.8 ± 1.7 mm/yr, supported by the recorded focal mechanisms in this area (Figure 4.6). This dramatic extension is interpreted as a very recent tectonic movement, probably since the Pleistocene, which is coeval with the onset of the

transtensional regime of the Tarera-Adiuna fault and the Paniai fault leading to the collapse of Cenderawasih Bay (Bailly et al., 2009).

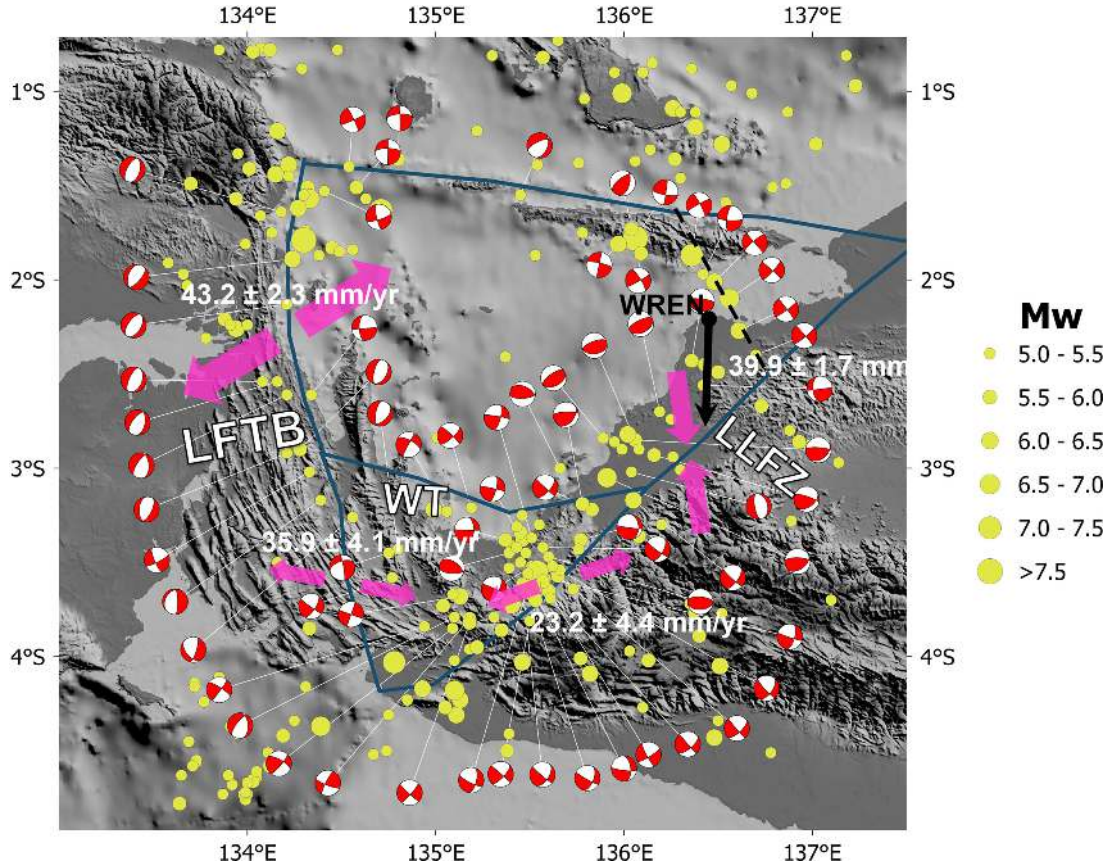


Figure 4.6: The distribution of the earthquake focal mechanisms in Cenderawasih Bay region (rectangle area A in Figure 4.5a). The seismicity data are derived from the global centroid moment tensor catalog with depth less than 50 km and $M_w > 5$ from 1976 to 2021. The purple arrows show the undergoing oblique compression and extension along the active block boundaries represented by the solid line. The black solid arrow represents the global positioning system velocity WREN, which was excluded in the inversion, and the dashed line represents the locus of the unmapped boundary based on the seismicity distribution. The bathymetry data are from <https://www.gebco.net/>. The modeled earthquake slip vectors for this region are shown in Figure B.3c of Supporting Information B.

The nature of this extension may be closely related to the evolution of Cenderawasih Bay and is a matter of some debate. One hypothesis involves tectonic escape caused by the rollback of the Seram Trench and is associated with the sinistral movement on the Tarera-Adiuna strike-slip fault. The other hypothesis is the anticlockwise

rotation of the Bird's Head block (BRHD) driven by the convergence between the Australian and Pacific Plates (i.e., the oblique convergence between BRHD and the Pacific Plate in the north pushes the top of the BRHD westward, while the oblique convergence with the Australian Plate in the south pushes the bottom of BRHD eastward) (Charlton, 2000b, 2010). Our kinematic evidence is more consistent with the second hypothesis, considering the estimated extension rate on the northern part of the Lengguru fault zone is significantly larger than that on the southern part. However, the anticlockwise rotation rate ($2.82 \pm 0.11^\circ/\text{Myr}$) of the Bird's Head block derived from our kinematic model is much smaller than that estimated by Charlton (2000b, 2010), which suggests that the rotation of the Bird's Head block is not the only driver of the Cenderawasih sphenochasm formation. The significant volume of sediments accumulated in Cenderawasih Bay and Waipoga Basin also indicates that the evolution of the embayment should have started before ~ 12 Ma rather than the Pliocene opening of the bay suggested by Babault et al. (2018).

The convergence rate on the northern Lowlands fault zone is larger than that on the southern part, whilst the fault-parallel rates are uniform along the entire fault zone, which has an average sinistral strike-slip rate of 36.5 ± 1.7 mm/yr (Figure 4.5a and 4.5b). This is consistent with the distribution of thrust and strike-slip earthquake focal mechanisms, as well as with the tectonic setting (Figure 4.1 and Figure 4.6). This uniform southwestward fault-parallel translation of blocks TABL and CEND provides geodetic evidence supporting the southwestward drift hypothesis for the formation of the Cenderawasih Bay sphenochasm put forward by François et al. (2016b), which suggested that the Weyland overthrust has migrated 25-km southwestward during the Late Miocene (Babault et al., 2018). This southwestward translation is consistent with the dextral strike-slip motion on the southwestern part of the Lengguru fault zone with an average slip rate of 24.1 ± 3.9 mm/yr, which is supported by geological and seismic evidence (Figure 4.6; Babault et al., 2018; Cloos et al., 2005; Dow and Sukanto, 1984; François et al., 2016b; Pubellier and Ego, 2002;

Stevens et al., 2002), as well as by the sinistral motion on the Lowlands fault (Figure 4.7; Babault et al., 2018; Cloos et al., 2005; Dow and Sukanto, 1984; François et al., 2016b; Pubellier and Ego, 2002; Stevens et al., 2002). Extensional earthquakes are distributed all along the entire Lengguru fault zone, but the dextral strike-slip earthquakes are primarily concentrated in the southwestern part. This seismicity pattern is in excellent agreement with our kinematic model. We deduce that the WSW drift of blocks CEND and TABL is accommodated mainly by the sinistral slip along the entire Lowlands fault zone, but is also partially accommodated by the dextral slip on the southern part of the Lengguru fault. The shift of the strike-slip style and the northward increasing extension rate on the Lengguru fault zone indicate that both driving mechanisms (Bird' Head rotation and southwestward drift of the Weyland overthrust) have been and still are active, contributing to the development of Cenderawasih Bay. We note that the sparsity of the GPS data in the TABL block results in large uncertainties on the estimated relative slip rates along the boundary faults.

4.6.4 Tectonic Regime Change Along the New Guinea Fold-And-Thrust Belt

The NGFTB covers much of the island of New Guinea, and our model predicts relative velocities across this belt that undergoes two different transitions from west to east. The relative motion along the NGFTB decreases from 25.8 ± 0.9 mm/yr at the western end of the belt to 7.1 ± 0.4 mm/yr at 141.2°E , then increases to 12.3 ± 0.6 mm/yr at the eastern end of the belt (Figure 4.6). Additionally, the direction of relative motion also exhibits a variation, from southwestward to westward then back to southwestward again, indicating a transition from oblique thrust to sinistral strike-slip and back to oblique thrust that is consistent with the observed earthquake focal mechanisms (Figure 4.7).

The NGFTB formed because of the diachronous collisional orogenesis result-

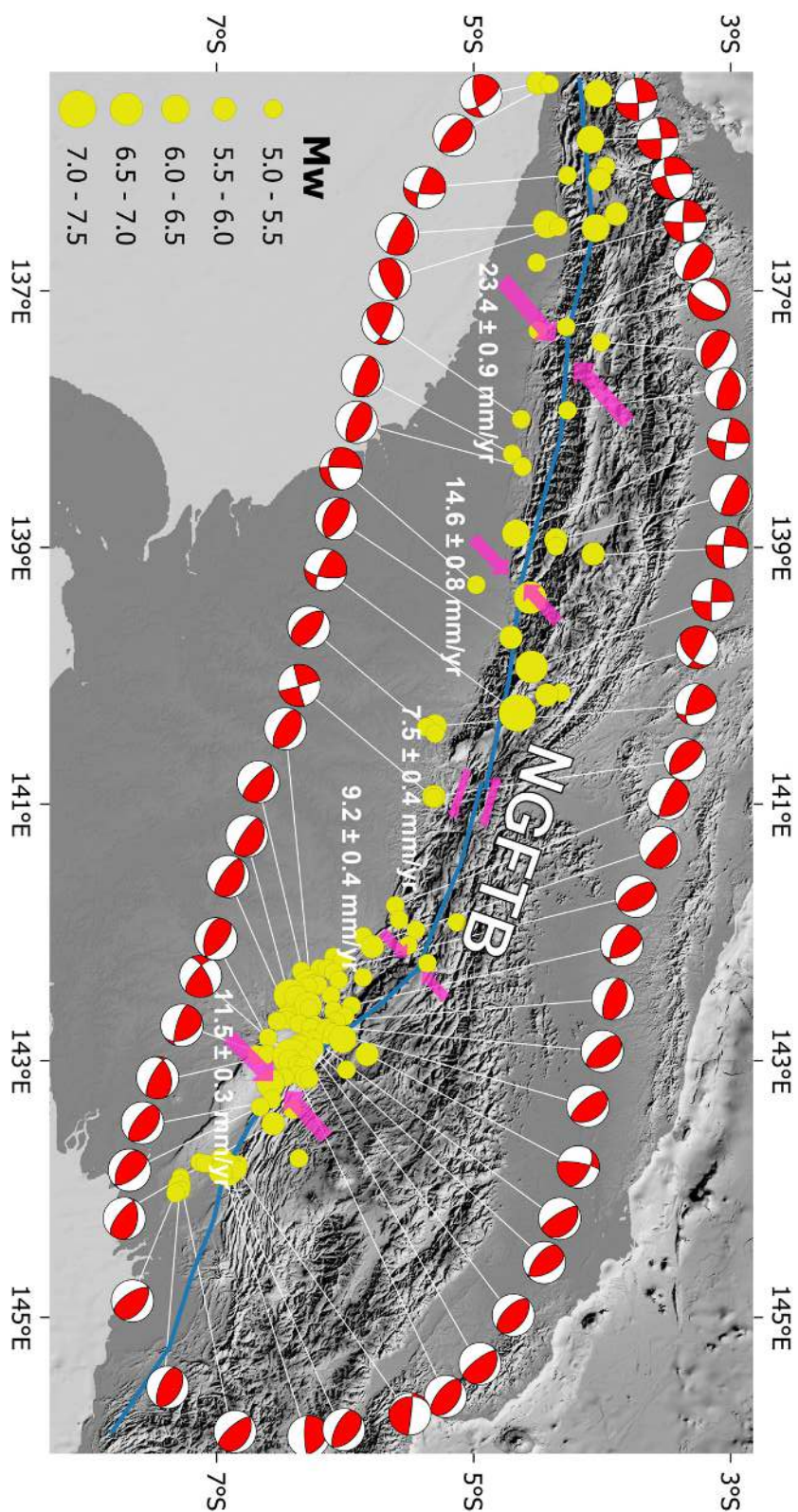


Figure 4.7: The distribution of the earthquake focal mechanisms in Cenderawasih Bay region (rectangle area B in Figure 4.4

Figure 4.7: b). The seismicity data are derived from the [GCMT](#) catalog, using events with depth less than 50 km and magnitude larger than five from 1976 to 2021. The arrows show the undergoing oblique compression and sinistral strike-slip along the active block boundaries represented by the solid line.

ing from the Melanesian arc-continent oblique collision that occurred in the Late Oligocene-Miocene, beginning from the west and propagating to the east ([Baldwin et al., 2012](#); [Cloos et al., 2005](#)). According to our decomposed relative motion results, the average convergence of the western part of the [NGFTB](#) (west of longitude 141°E) is ~ 10.6 mm/yr. The relative fault-normal motion decreases from 19.5 ± 0.6 to 1.4 ± 1.2 mm/yr toward the east. The average fault-parallel velocity is 13.5 ± 0.9 mm/yr (Figure 4.5). In the east segment, the average convergence is ~ 8.5 mm/yr with an increase of relative fault-normal motion from 2.2 ± 0.7 to 9.0 ± 0.5 mm/yr toward the east, and the average fault-parallel velocity is ~ 5.7 mm/yr. Geologic evidence indicates that the shortening across the western [NGFTB](#) may have already ceased at ~ 4 Mya, and the eastern segment is undergoing a shortening stage similar to that of the western segment prior to 4 Mya, implying that the convergence rate of the western [NGFTB](#) should be lower than that of the eastern [NGFTB](#) ([Bailly et al., 2009](#); [Baldwin et al., 2012](#); [Cloos et al., 2005](#); [Hill and Hall, 2003](#)). However, in our estimation, both fault-parallel and fault-normal rates on the western segment of the [NGFTB](#) are larger than those on the eastern segment, which suggests that the western [NGFTB](#) also accommodates oblique shortening from some other tectonic activity. This seems likely, considering that the westernmost [NGFTB](#) conjuncts with multiple active diffuse fault zones, including the Tarera-Adiuna fault zone, Lowlands fault zone, and Paniai fault zone, which accommodate transtensional deformation from the rotation of the Bird's Head block and the southwestward drift of Weyland overthrust ([François et al., 2016b](#); [Stevens et al., 2002](#); [Watkinson and Hall, 2017](#)). The relatively large oblique motion on the western end of the [NGFTB](#) is more likely the consequence of the combination of the sinistral movement along these intersecting fault zones rather than the collisional orogenesis. In addition, the low convergence

rate we obtained for the center NGFTB that increases toward the east is consistent with prior studies, in the sense that the east NGFTB is still active. However, in the central section, our geodetic results suggest that the NGFTB is still undergoing slow convergence rather than having ceased shortening completely.

4.7 Conclusions

This study is the first attempt to give the entire Indonesia–Australia–New Guinea collision zone a broad quantitative interpretation by utilizing over 200 available GPS observations and 492 earthquake slip vectors. As one of the most tectonically complicated and seismically active regions globally, the kinematic framework for the deformation in this boundary zone has hitherto been piecemeal. The new GPS velocity field has filled important knowledge gaps in the Banda Sea and West New Guinea areas and updated previous studies in the Sunda–Banda arc and Papua New Guinea. Our broad-scale kinematic model emphasizes the motion change along the active boundary faults, which is in some cases quite pronounced, thereby enhancing our understanding of the evolution of some large tectonic structures. Although the estimated kinematic results of the first-order block properties presented in this study may not account for some localized effects that may require more detailed microblock parameterization, we believe they are useful for understanding the broad-scale tectonics and provide a useful framework for further, more detailed studies.

We suggest that the western New Guinea Fold-and-Thrust Belt accommodates larger convergence (between 4 and 18 mm/yr) than the eastern segment of NGFTB (between 3 and 11 mm/yr), which is mainly caused by the stress transfer from the highly active Tarera–Aiduna, Lowlands and Paniai fault zones. The combined effect of these active faults is diminished eastward, and the shortening accommodated on the NGFTB becomes the only driving mechanism of the ongoing convergence, increasing from the middle segment ($\sim 138^{\circ}\text{E}$ to 142°E) to the eastern NGFTB ($\sim 142^{\circ}\text{E}$ to 144°E). Hence, we can observe a double shift in the tectonic regime along this

~2,000 km highland belt. The estimated rotation rate of the Bird's Head block and the slip style transitions along the Lowlands and Lengguru fault zones provide the geodetic evidence that the formation of the Cenderawasih Bay sphenochasm is due to both the interaction of both Bird's Head rotation and the southwestward drift of the Weyland Overthrust, and that both these mechanisms continue to be active.

One of the important reasons for developing our kinematic block model is to guide the assessment of seismic hazards. Recent seismic hazard assessments for both Indonesia ([Irsyam et al., 2020](#)) and PNG ([Ghasemi et al., 2016, 2020](#)) make extensive use of such tectonic block models to refine estimates of seismic hazard. In both cases, these have revealed areas where the hazard level was significantly higher than earlier assessments done without the benefit of detailed kinematic block models. For example, the high rate and dramatic eastward increase in the rate of convergence of the Ramu-Markham Fault, which passes near PNG's second-largest city, Lae, confirms the very high seismic hazard inferred by [Ghasemi et al. \(2020\)](#), based on the earlier kinematic block models of [Wallace et al. \(2014\)](#) and [Koulali et al. \(2015\)](#).

The plausible kinematic scenario presented by our model is consistent with other seismic and geological evidence, whereas we also note that some blocks are not fully explained; the relatively large χ_n^2 values for some blocks imply the potential existence of other micro-blocks in these regions. The lack of observations in some blocks leads to large uncertainty on some estimated block motions. The locking coefficient of the block-bounding active faults in the West New Guinea region is also largely unresolved due to the lack of nearby [GPS](#) observations. Therefore, to better investigate the potential existence of active structures and quantify the seismic hazard posed by these structures, and provide the local populations with information about the likely nature of future earthquakes, more dense, long-term, and continuous [GPS](#) observations are essential.

4.8 Acknowledgments

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Resolving Microplate Kinematics in the Western Banda Arc Using GPS Observations and Multiscale Strain Modeling

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H. Nugroho,¹ M. S. Miller¹, S. McClusky^{1,2}, B. Hejrani^{1,2}, S. Mousavi¹, R.
Fernandes^{3,4}, E. Soares,⁵ F. J. G. Jones⁵, and G. P. Almeida⁵

Foreword

Chapter 5 builds on the regional framework established in Chapter 4 by examining deformation within the Timor region at the scale of individual tectonic blocks. Using GPS-based block modelling, we partition the study area into discrete micro-blocks to better resolve localised kinematics, strain accumulation, and fault slip behaviour that are not captured in broader, plate-scale analyses.

This chapter is motivated by multiple lines of evidence for arc-parallel deformation within the Timor collision system. Seismological observations, including an earthquake located in the proximal hanging wall of the backarc thrust, indicate east-

¹Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia.

²Geoscience Australia, Symonston, ACT, 2609, Australia.

³University of Beira Interior, Covilhã, Portugal

⁴Instituto Dom Luís, Covilhã, Portugal

⁵Instituto de Geociências de Timor-Leste (IGTL), Dili, Timor-Leste.

ward transport of crustal material—particularly the extinct volcanic complexes of northern Alor and Wetar—parallel to the Banda Arc. At a broader scale, regional GPS studies suggest that the Timor Block exhibits a similar pattern of arc-parallel motion relative to the Sunda Arc.

To date, most GPS-based interpretations have attributed this arc-parallel motion primarily to slip along major block-bounding faults. For example, differential uplift rates across the Semaui Fault—between Kupang (~ 0.3 mm/yr; [Jouannic et al., 1988](#)) and Rote (~ 1.5 mm/yr; [Roosmawati and Harris, 2009](#))—highlight the significance of this structure in accommodating deformation. However, multiple lines of evidence suggest that deformation is not confined to block boundaries. Seismicity patterns, including the 2015 Alor earthquake sequence, together with field-based observations of arc-parallel extension and short-wavelength differential uplift in Timor-Leste and Atauro (e.g., [Chappell and Veeh, 1978](#); [Cox, 2009](#); [Duffy et al., 2013](#); [Ely et al., 2011](#)), indicate that the Timor Block is undergoing significant internal deformation.

Motivated by these observations, we develop a kinematic block model that integrates GPS observations, earthquake slip vectors, and mapped fault geometries. The model incorporates newly defined micro-blocks across Timor and its surrounding regions, including the Alor fault identified in Chapter 3 as an additional block boundary. Our preferred solution indicates that the present-day deformation is best described by a system of six micro-blocks.

To complement the block modelling approach, we apply spherical wavelet-based strain-rate estimation to resolve deformation across multiple spatial scales. This allows us to capture both rigid block rotations and distributed strain within a unified framework, producing a continuous velocity field and corresponding horizontal strain-rate field. Together, these results provide new insight into the kinematics of the Timor Block and the processes driving deformation within the broader Banda Arc system.

5.1 Abstract

We present new constraints on crustal kinematics in the Timor Block using dense Global Positioning System (GPS) measurements and multiscale modeling. Building on previous block models, we incorporate more than 15 years of campaign and semi-permanent GPS data, significantly improving spatial coverage in areas that were previously poorly resolved. The expanded dataset allows us to subdivide the previously defined Timor Block into six distinct kinematic blocks, refining block boundaries and fault geometries. We apply a combined approach using elastic block modeling and spherical wavelet-based strain-rate estimation to resolve both discrete block rotations and distributed deformation. The updated model reveals variable slip rates across fault segments, with the highest slip rates occurring along back-arc structures and lower rates in central parts of the island. The results show systematic variations in block rotation rates between the western and eastern domains, reflecting complex strain accommodation associated with the accretion of the Timor microcontinent to the Banda forearc system. Horizontal strain rates highlight localised zones of strain accumulation along several mapped fault zones, while other areas show relatively limited internal deformation. These results indicate that the Timor Block represents an actively reorganizing segment of the broader Banda Arc plate boundary, where the dominant style of deformation is consistent with a transition from subduction-dominated tectonics in the west to collision-driven distributed deformation in the east. The partitioning of deformation among multiple microblocks provides new insights into the present state of plate boundary reorganization within the western Banda Arc and its transition from subduction to continental collision. Collectively, these findings provide improved constraints on the spatial distribution of active deformation and establish a more robust kinematic framework for future seismic hazard assessments in the Timor collision zone.

Keywords: Crustal deformation, GPS, Kinematic block model, Spherical wavelet method, Timor block, Banda arc

Key Points

- We refine the Timor block model by introducing six micro-blocks and adjusting the boundary to incorporate the fault on Alor Island identified from the 2015 Alor earthquake (M_w 6.2).
- Our model reveals a mix of tectonic forces, with the region from Flores to northern Wetar experiencing the fastest motion at ~ 53 mm/yr, left-lateral strike-slip in the Timor Trough, horizontal shortening north of Wetar due to plate convergence, and extension at the eastern boundary with the North-and-East of Timor block ([NETI](#)).
- Crustal deformation from the Timor Trough to the back-arc thrust is also accommodated by the northern Belu Fault, in addition to the Semaui Fault.
- Changes in rotation direction and rates are observed, with counterclockwise rotation in the west and clockwise rotation in the east, likely influenced by the irregular geometry of the collisional margin.

5.2 Introduction

Global Positioning System ([GPS](#))-based methods are powerful tools to study the crustal movements of the Earth over decadal time scales. These methods help to constrain the spatial distribution of the deformation, its driving mechanisms, and the geometry of lithospheric boundaries in the observed region. For almost three decades, numerous studies have been conducted in Indonesia and Southeast Asia, revealing plate and block boundaries, identifying stable and deforming regions, and providing critical insights into where and how tectonic energy might be released in the future, potentially leading to destructive seismic events (cf. [Tregoning et al., 1994](#); [Genrich et al., 1996](#); [Puntodewo et al., 1994](#); [Walpersdorf et al., 1998b,a](#); [Bock et al., 2003](#); [Simons et al., 2007](#); [Nugroho et al., 2009](#); [Koulali et al., 2015, 2016, 2017](#); [Zhao et al., 2023](#)).

As a result of the arc–continent collision, the Banda Arc is undergoing significant crustal deformation (Figure 5.1a). Koulali et al. (2016) modeled this region and identified five fault-bounded lithospheric blocks extending from East Java to the Tanimbar Islands (Figure 5.1b). However, they were unable to delineate the block boundary to the north of the Timor Block due to the lack of dense or long-term GPS observations in the region.

Recently, Zhao et al. (2023) defined 23 elastic blocks based on previous models with some adjustments to the pre-existing blocks and the introduction of new blocks covering the extensive 5000 km stretch of the Indonesia-Australia-New Guinea collision zone. While the slip rates and strain along the boundaries of the Timor Block have been updated, it is still modeled as a single rigid block.

This approach rooted in previous studies, where the Timor Block—extending from eastern Sumba to the Tanimbar Islands—was modeled as a single rigid body, primarily due to the sparse distribution of geodetic observations across the region (e.g., Koulali et al., 2016; Zhao et al., 2023). We use the GPS data acquired during our 2018 and 2019 campaign surveys across Timor-Leste (Figure C.1 & Table C.1) — along with unpublished data from colocated sites observed in 2005 and 2014 — to reassess this assumption. We apply block modeling to quantify strain accumulation along fault boundaries and generate a continuous velocity field from discrete GPS velocity data. From this field, we derive the horizontal strain-rate distribution using a wavelet-based approach following Tape et al. (2009). This method allows us to analyse deformation across various spatial scales in the western Banda Arc region, revealing the different levels of deformation in the transition from subduction to collision eastward along strike between Rote and Timor Island.

5.3 Tectonic Background

The Banda arc region is characterized by the convergence of four major plates: the Australian, Pacific, Philippine Sea, and Sunda Plate (Hamilton, 1979; Hinschberger

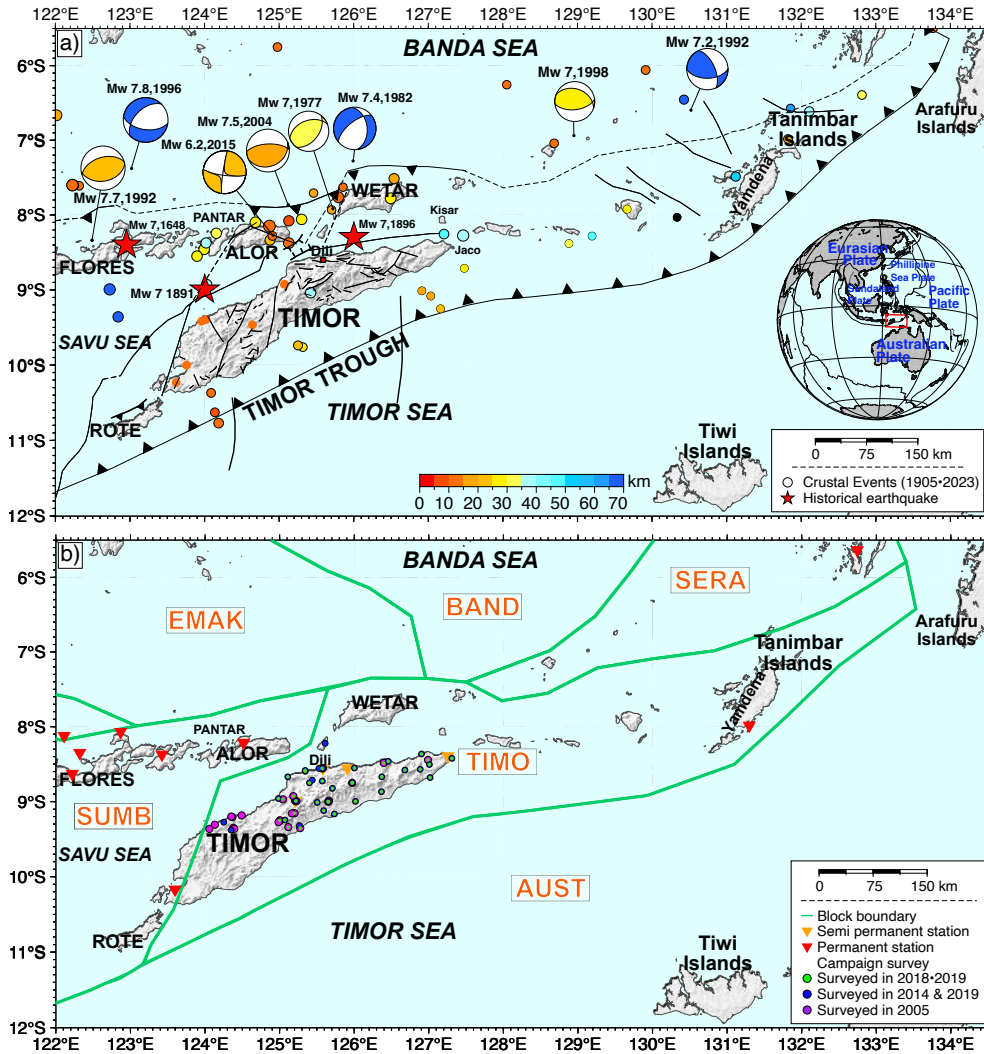


Figure 5.1: Tectonic and block boundaries maps in the western Banda region. a) Faults are based upon those in the literature (McCaffrey, 1988; Kaneko et al., 2007; Charlton et al., 1991; Duffy et al., 2013; Rosidi et al., 1979; Martinez Duran et al., 2020) and seismicity of Timor Island and surrounding area. Onshore fault traces are shown as solid lines to provide tectonic context, while inferred offshore tectonic boundaries are shown as dashed lines. Detailed fault names, classifications, and structural interpretations are provided in Figure 5.2. Historical earthquakes (1000-1903) with $M_w \geq 6.2$ (Albini et al., 2014; Griffin et al., 2019; Musson, 2012, in red stars) and instrumental era earthquake (1905-2023) with $M_w \geq 5.5$ are acquired from the National Earthquake Information Center (NEIC) catalog (Benz, 2017, colored circles). Focal mechanisms $M_w \geq 6.5$ are from Global Centroid Moment Tensor Project (Dziewoński et al., 1981; Ekström et al., 2012). Focal mechanism of M_w 6.2 2015 Alor earthquake is from Nugroho et al. (2024). b) Block boundaries adopted from the previous model of Zhao et al. (2023), including the Timor block (TIMO), Australian Plate (AUST), Sumba block (SUMB), East Makassar block (EMAK), Banda block (BAND) and Seram block (SERA). The map shows the spatial distribution of representative GPS stations, color-coded as first-order campaign, second-order campaign, and continuous sites; see Table C.5 for the complete station list.

et al., 2005; Simons et al., 2007; Hall, 2002, 2012, Figure 5.1). Extending east from Sumba (Figure 5.1), the dominant tectonic process involves the transition from the subduction of oceanic crust beneath island arc in the west to arc-continent collision in the east (Harris, 2011; Ely and Sandiford, 2010; Nugroho et al., 2009; Porritt et al., 2016; Shulgin et al., 2009). The collision of the Banda Arc with the Australian Plate, which began during the Late Miocene (Harris, 2011; Hall, 2011; Roosmawati and Harris, 2009), produced the Timor Trough, which is underlain by continental lithosphere (e.g., Audley-Charles, 2004). Underthrusting of the continental margin led to the formation of a complex fold and thrust belt involving a variety of mostly non-volcanic rocks from the Australian continental margin, the Asian affinity Banda Terrane, and more recent synorogenic deposits. These areas represent zones of active convergence where strain is distributed throughout a wide zone of active deformation stretching from the Australian continental margin to the back-arc region. The interaction between these distinct geological units plays a crucial role in influencing the behavior of active faults (Harris, 2011; Keep and Haig, 2010; Coudurier-Curveur et al., 2021; Baillie et al., 2020; Martinez Duran et al., 2020).

In west Timor, crustal deformation is also characterized by strike-slip deformation associated with the 1975 Kupang earthquake (Tjia, 1983) and geological field mapping from Timor-Leste (Duffy et al., 2013). One notable fault along the western edge of Timor and Semaui and Rote Islands region is Semaui Fault (Figure 5.1b), recognized as a significant active fault zone (Karig et al., 1987; Roosmawati and Harris, 2009; Barber et al., 1986; Harris and Major, 2017; Koulali et al., 2016), stretching along the western edge of Timor and through the Semaui, Rote and Alor Islands serves as a connection between the Timor Trough and the back-arc thrust system.

From the interpretation and analysis of broadband BandaSeis 2D seismic data, two elongated faults trending NE were identified offshore of Timor (Martinez Duran et al., 2020). Both faults: the Nunkolo and Manatuto structures are imaged in seismic reflection data on the southern side of the Timor Trough (Figure 5.1 & 5.2). Their

deeper geometry and lateral continuity remain uncertain; they are interpreted here as expressions of inherited basement structures within the underthrust passive margin, which may influence structural style and detachment levels within the foreland basin rather than representing discrete faults cutting across the entire accretionary prism.

In the northern region, deformation is expressed through the Flores-Wetar back-arc thrust system, including Wetar-Atauro Fault, resulting from the Australian plate overriding the Banda Sea oceanic crust (Silver et al., 1983; McCaffrey, 1988; Breen et al., 1989; Snyder et al., 1996). The advance of the Australian continental crust into the Asian forearc led to the formation of the Wetar Suture to the north of Timor Island as a major thrust zone developed early in the collision phase (Audley-Charles, 1981, 2011; Breen et al., 1989; Snyder et al., 1996; Richardson and Blundell, 1996).

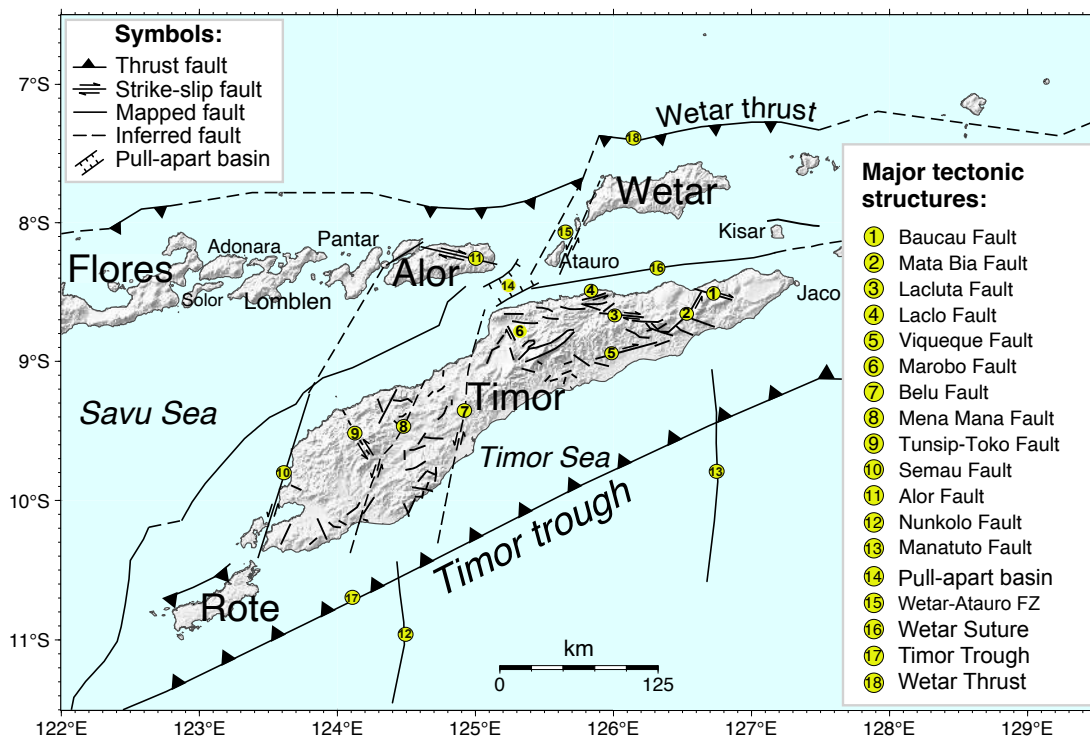


Figure 5.2: Fault map of Timor Island and surrounding area compiled from published geological and geophysical studies (Kaneko et al., 2007; Charlton et al., 1991; Duffy et al., 2013; Rosidi et al., 1979; Martinez Duran et al., 2020), with additional structures identified in this study (Nugroho et al., 2024).

5.4 Data

This study utilizes a combination of data from permanent networks obtained from the Indonesian Geospatial Information Agency (BIG) and the International GNSS Service (IGS) network, along with data from a semi-permanent station installed in Dili, as well as legacy campaign data from 2005 that were previously unpublished, and new campaign data in 2014, 2018 and 2019. In addition, we also use earthquake slip vectors from Global Centroid Moment Tensor (GCMT) and from our recent study of a sequence of earthquakes on Alor island (Nugroho et al., 2024).

Faults are mapped from literature sources (Kaneko et al., 2007; Charlton et al., 1991; Duffy et al., 2013; Rosidi et al., 1979; Martinez Duran et al., 2020). Normal faults have been identified in many parts of Timor (Standley and Harris, 2009, Figure 5.2). The Laclo Fault, a normal fault in the northern part of the island, has been recognized and mapped (Berry and Grady, 1981; Harris, 2011). Detailed structural mapping in Timor-Leste identified the Marobo Fault, Mata-Bia Fault, Lacluta Fault, and Viqueque Fault (Duffy et al., 2013, Figure 5.2). We incorporated the fault on Alor Island, identified from the M_w 6.2 2015 Alor earthquake (Nugroho et al., 2024), as a new block boundary.

5.4.1 GPS Data

A summary of the GPS campaign surveys used in this study is provided in Table 5.1. Detailed information for each campaign, including station occupations and observation periods, is presented in Tables C.1-C.5.

We use unpublished GPS campaign data collected from 12 sites with the first-order benchmarks in Timor-Leste in 2005 (see Table C.1, Figure C.1 & C.2 for details). The data of each station spans four to five days, except for the Maliana (MLNA) station (Table C.1). Additionally, we acquired short-spanned data (with time windows of less than 8 hours) from campaigns to support Light Detection and Ranging (LiDAR) surveys in Timor-Leste in 2014 (Table C.2).

In 2018 and 2019, we conducted comprehensive GPS campaigns across Timor-Leste, collecting data from 40 stations, including 11 sites with the first-order GPS benchmarks colocated with 2005 campaign sites (Table C.3; Figure C.1 & C.2). We also installed and maintained four semi-permanent stations (Table C.3; Figure C.1 & C.2), however only the DILI station had data from multiple epochs, and it was the only one used.

GPS data were collected using a Trimble 5700 GPS receiver equipped with a Zephyr antenna. To obtain sufficient positioning accuracy and reliable ambiguity resolution, a minimum recording duration of 8 hours was set for each observation session. A tripod was not required for the GPS campaign on the first-order benchmarks, as these benchmarks had standard antenna mounting screws attached to the top of each pillar, allowing direct and repeatable antenna installation.

The primary GPS campaigns were carried out on 31 sites spanning from July to early September 2019 (see Table C.3 & C.4). Each session was limited to under 12 hours for every site.

Table 5.1: Summary of GPS campaign surveys in Timor Leste used in this study. The complete list of station names and coordinates is provided in Tables C.1-C.5.

Year	Observation Period (DOY)	Campaign Duration	Number of Sites	Survey Coverage
2005	DOY: 216-322	35 days	12	Unpublished data
2014	DOY: 240-285	21 days	29	Unpublished data
2018	DOY: 156-365	4 days	4	First Primary field campaign
2019	DOY: 001-299	30 days	31	Second Primary field campaign

Note: The observation period (DOY) represents the temporal span between the earliest and latest observations included in the dataset and does not correspond to the continuous duration of field operations. For the 2018 and 2019 surveys, the observation period includes continuous observations from semi-permanent stations installed at Dili and Maliana.

The majority of the benchmarks occupied during this campaign were second-order monuments, which are typically constructed for medium-precision geodetic applications and temporary or semi-permanent deployments. Unlike first-order

monuments, which are deeply anchored, permanently installed pillars designed to minimize long-term instability and allow direct antenna mounting, second-order monuments generally consist of shallow-drilled marks, concrete pads, or surface-installed pillars that may require tripod mounting and forced-centering adapters. Although not as mechanically robust as first-order monuments, second-order benchmarks are suitable for repeated GPS observations and provide sufficient short- to medium-term stability for campaign-style surveys, particularly in remote or logistically challenging environments where permanent monument installation is impractical.

We also acquired continuous GPS data spanning five years, from 2015 to 2019 from the Geospatial Information Agency (Indonesian: Badan Informasi Geospasial, abbreviation: BIG). The station distribution is shown in Figure C.1 and C.2, marked with red symbols. GPS observation data are provided in C.5. We use the data from these continuous stations as regional control points, in addition to the IGS network.

5.4.2 Earthquake Slip Vectors

We also utilized earthquake slip vectors to constrain the azimuth of block motions and the Eulerian pole of each block (Aki and Richards, 1980; DeMets et al., 1990, 1994; Koulali et al., 2015, 2016; Tregoning and McQueen, 2001; Zhao et al., 2023). Except for the slip vector from the M_w 6.2 Alor earthquake (Figure 5.1a; Nugroho et al. (2024)), we calculated a total of 111 earthquake slip vectors from focal mechanisms of crustal earthquakes published in the Global Centroid Moment Tensor (GCMT) catalog (Dziwowski et al., 1981; Ekström et al., 2012) for events shallower than 70 km and $M_w > 5.5$ from 1976 to 2023 (Figure C.3 and C.4; Table C.6).

5.5 Methods

5.5.1 Data Processing and Velocity Estimation

We used [GAMIT/GLOBK](#) version 10.70 ([Herring et al., 2015a](#)) to process and analyze the [GPS](#) data following a two-step approach ([Dong et al., 1998](#); [McClusky et al., 2000](#); [Reilinger et al., 2006](#)). This software is a high-precision Global Navigation Satellite System ([GNSS](#)) data processing tool, widely applied for monitoring regional and global plate motion and for studying the dynamics of plate boundaries and interior, including analysis of crustal deformation (e.g., [Altamimi et al., 2012, 2016](#); [Koulali et al., 2015, 2016, 2017](#); [McClusky et al., 2000](#); [Reilinger et al., 2006](#)). [GAMIT](#) incorporates difference-operator algorithms to map the carrier beat phases into single and double difference phases. This workflow allows us to accurately identify and eliminate the dominant sources of error, including satellite clock and orbit errors, localized atmospheric errors, and receiver clock errors.

Prior to combining the solution, most biases and errors, commonly due to antenna changes or seismic events (e.g., [Herring et al., 2010](#); [Tregoning et al., 2013](#); [Blewitt et al., 2016](#); [Schmid and Rothacher, 2003](#)), have to be eliminated. [GLOBK](#) can neither correct deficiencies nor resolve phase ambiguities. An example of a jump in the [GPS](#) time series due to an earthquake, and its correction can be viewed in [Figure C.5](#). In the example, station Kalabahi (CKAL) recorded the effect of earthquake event with magnitude M_w 6.2 occurred on Alor Island on November 3, 2015. We use an empirical formula that approximates the radius of influence of an earthquake following [Herring et al. \(2016\)](#):

$$d = 2.5 \times 10^{-3} \times 5^M \quad (5.1)$$

with M representing the earthquake magnitude as provided by the [USGS](#) National Earthquake Information Center ([NEIC](#)); all stations within d kilometers of the epicenter are subsequently analyzed by fitting the GPS time series, accounting for all iden-

tified offsets and estimating the coseismic displacement associated with the earthquake.

5.5.2 Spherical wavelet-based modeling of Velocity and Strain-Rate

To better resolve the kinematics in the Banda Arc region, where multi-scale spatial deformation occurs due to the transition from subduction to collision (e.g., [Miller et al., 2016](#); [Harris, 1991, 2011](#); [Shulgin et al., 2009](#); [Duffy et al., 2013](#)), we generate a continuous velocity field based on discrete [GPS](#) velocities and subsequently derive the horizontal strain-rate fields (Figure 5.3). Our methodology employs a wavelet-based multiscale approach, as outlined in [Tape et al. \(2009\)](#), which accounts for the irregular spacing of [GPS](#) stations and can capture details about crustal movement and deformation across various spatial scales not available with block modeling alone. This method has been used to derive strain rates at both continental and regional scales (e.g., [Serpelloni et al., 2022](#); [Yuan et al., 2023](#); [Gao et al., 2018](#); [Wu et al., 2018](#)).

As described in [Tape et al. \(2009\)](#), spatial scale is characterized by a wavelet order (q), where a higher resolution of wavelets (i.e., a higher q value) corresponds to a region of denser stations. Conversely, lower wavelet resolutions (lower q values) are associated with sparser station distributions. The reasonable range of q values typically falls between 7 and 9, corresponding to length scales of approximately 55 km and 14 km, respectively ([Serpelloni et al., 2022](#)). In our study area, q values range from 7 to 8 (~ 55 km to ~ 27 km; Figure C.6). To achieve comprehensive coverage of the onshore study region, we use maximum spatial scale (q_{max}) value of 7, which corresponds to ~ 55 km. This results in a lower spatial resolution in West Timor, Rote, Pantar, and part of Wetar and Alor Island, while maintaining higher resolutions in the central to eastern parts of Timor and Flores (Figure C.6 and 5.1a).

The wavelet-derived velocity and strain-rate fields are calculated directly from the observed [GPS](#) velocities and are independent of the subsequent block-model parameterization. Thus, these fields represent the continuous [GPS](#)-derived deformation

field prior to the removal of block motions or fault-slip contributions. They should not be interpreted as residual fields from the block model. Residual velocity and strain-rate fields are instead calculated separately from the preferred block model by comparing the observed [GPS](#) velocities with the model-predicted velocities.

5.5.3 Kinematic Block Modeling

For reference, the fault names and corresponding numbered fault segments discussed from this section onward are shown in [Figure 5.2](#).

We utilized [GPS](#) data from 128 sites covering the Timor Block and its adjacent blocks ([Table C.5](#)). Among those, 40 [GPS](#) velocity vectors are newly processed data acquired from 40 sites in Timor Island from 2005, 2014, 2018, and 2019 campaign surveys and from semi-permanent sites and continuous [GPS](#) (cGPS). Details of the data including campaign survey date, colocation sites and epochs are in [Table C.1–C.6](#).

We used the block modeling software TDEFNODE, as described by [McCaffrey \(2009\)](#), to model interseismic slip. TDEFNODE uses [GPS](#) surface velocity data and fault geometry to estimate block rotation rates, slip rates, and locking fractions. It also predicts surface velocities from the modeled parameters allowing comparison with observations.

The best-fit parameters are evaluated by comparing the modeled surface velocities with the observed surface velocities (e.g., [Figure 5.4](#)) and selecting parameter sets that minimize the differences between the two ([McCaffrey, 2009](#)). Slip rates are determined from the estimation of each block's Euler pole with reference to a chosen stationary block (i.e., the Australian Plate) and velocity of each block from the input [GPS](#) data. TDEFNODE has been widely used to model interseismic deformation, block rotations, fault slip rates, and fault coupling across active plate boundaries (e.g., [Graham et al., 2014](#); [Koulali et al., 2015, 2016](#); [DiZio, 2016](#); [Koulali et al., 2017](#); [Wallace et al., 2017](#); [Li and Freymueller, 2018](#); [Zhao et al., 2022, 2023](#)).

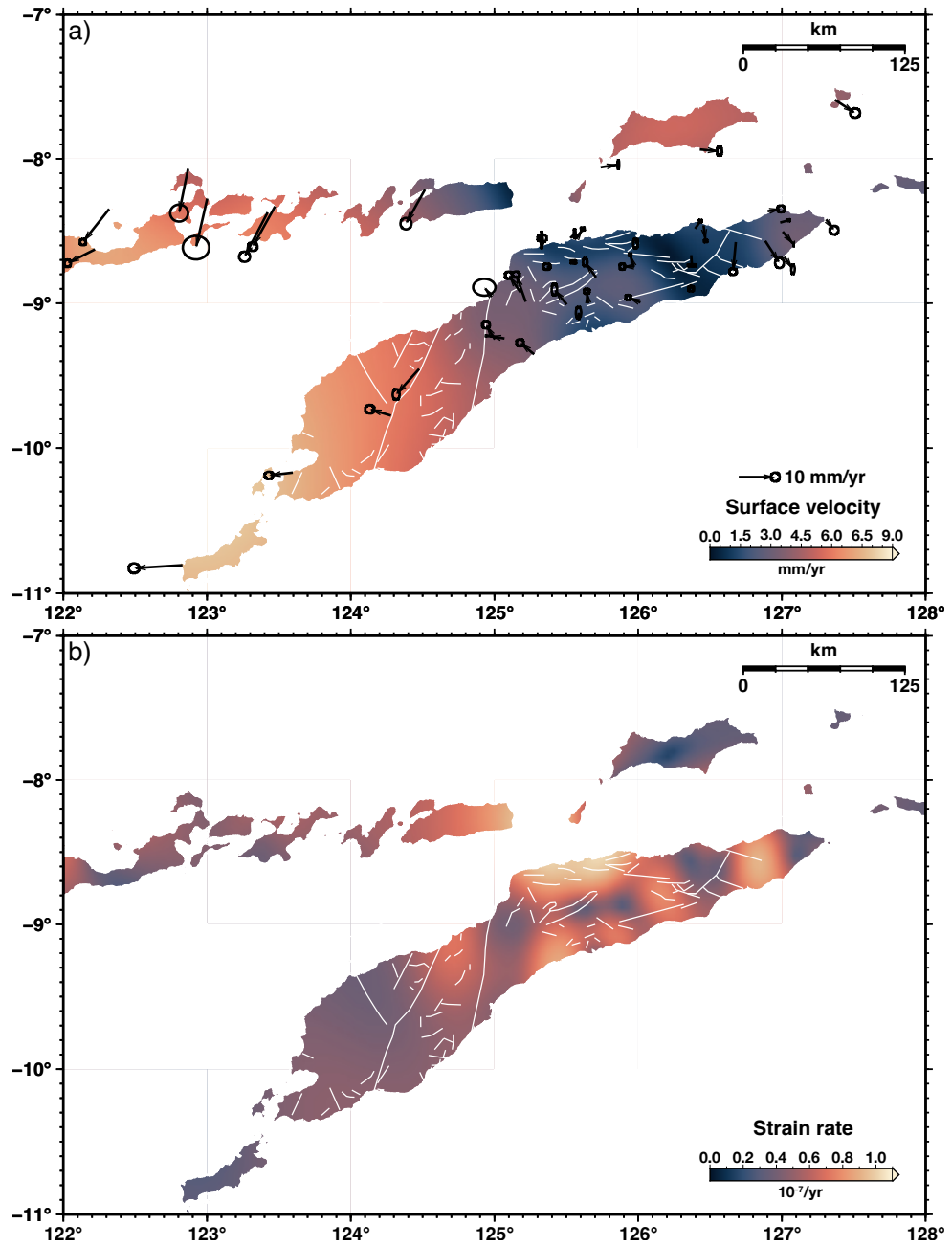


Figure 5.3: Results of the multi-scale estimation of surface velocity fields after removal of the reference-frame rotation, showing the resulting site velocities (a) and the calculated strain-rate field (b) derived from the observed [GPS](#) velocities. These are wavelet-derived fields and are not residuals from the block model. Faults are presented as white lines. For detailed fault names, fault classifications, and tectonic features, please refer to Figure [5.2](#).

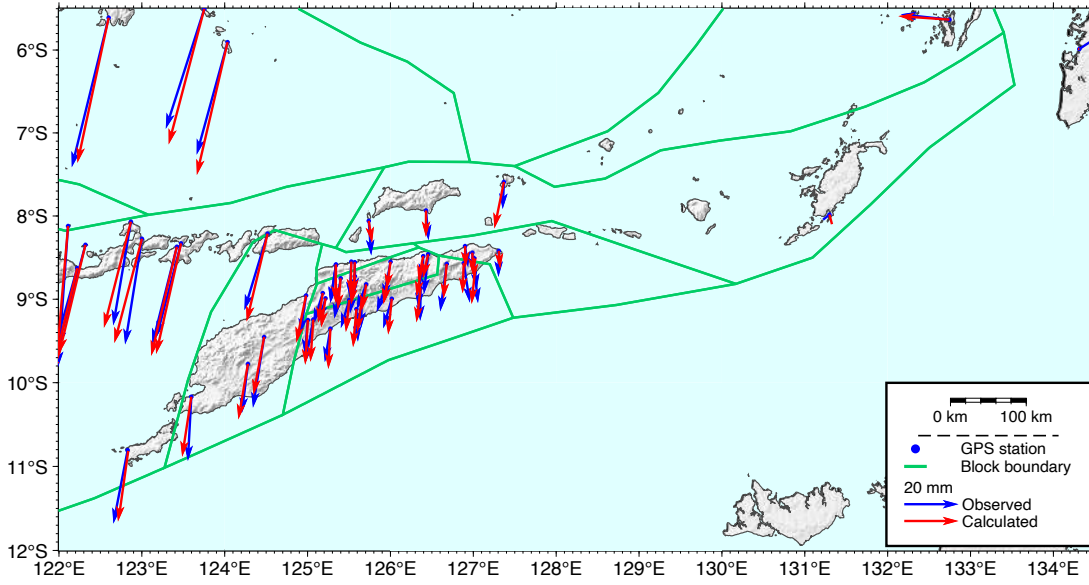


Figure 5.4: [GPS](#) velocity vectors plotted in an Australian Plate reference frame. Blue and red arrows show observed and calculated velocities, respectively. Green lines indicate proposed block boundaries.

To evaluate whether the internal segmentation of the Timor Block is supported by the [GPS](#) observations, we constructed two nested kinematic models. The first model represents Timor as a single rigid block, while the second model introduces an additional internal block boundary. All external block boundaries, fault geometries, locking depths, and other model parameters were kept identical between the two models, with the only additional complexity being the introduction of the internal boundary. The statistical significance of the improvement provided by the additional internal block was assessed using an F-test based on the reduction in Data χ^2 . The F-statistic is computed as:

$$F = \frac{(\chi_1^2 - \chi_2^2) / (k_2 - k_1)}{\chi_2^2 / (N - k_2)} \quad (5.2)$$

where χ_1^2 and χ_2^2 are the Data χ^2 values for the single-block and subdivided-block models, respectively; k_1 and k_2 are the corresponding numbers of estimated model parameters; and N is the total number of [GPS](#) velocity components used in the inversion. The null hypothesis is that the additional internal block boundary does not

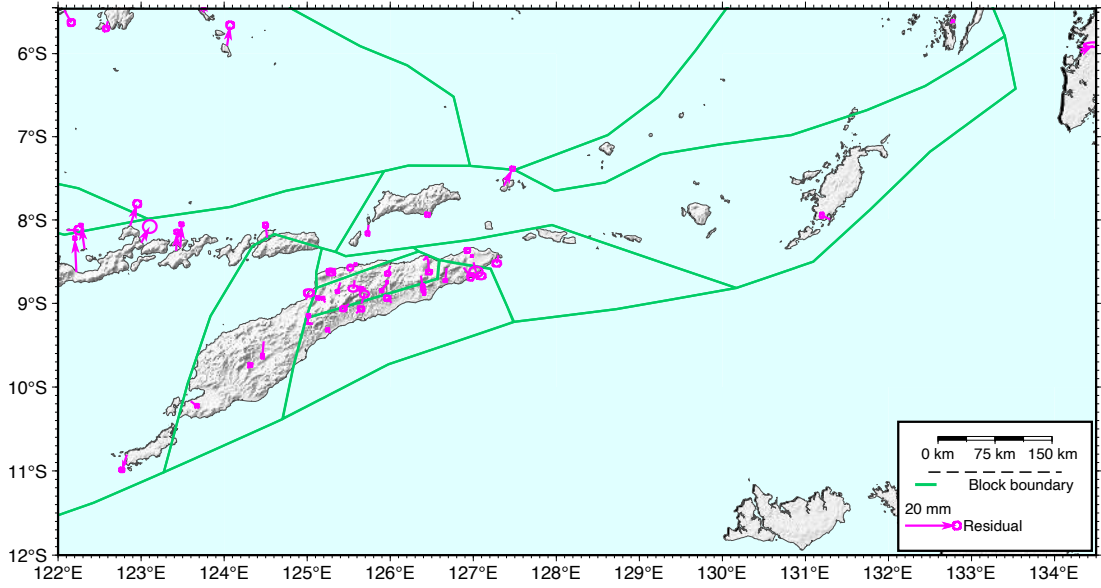


Figure 5.5: Residual of horizontal GPS velocity fields and their associated uncertainties are presented using pink arrows and ellipses.

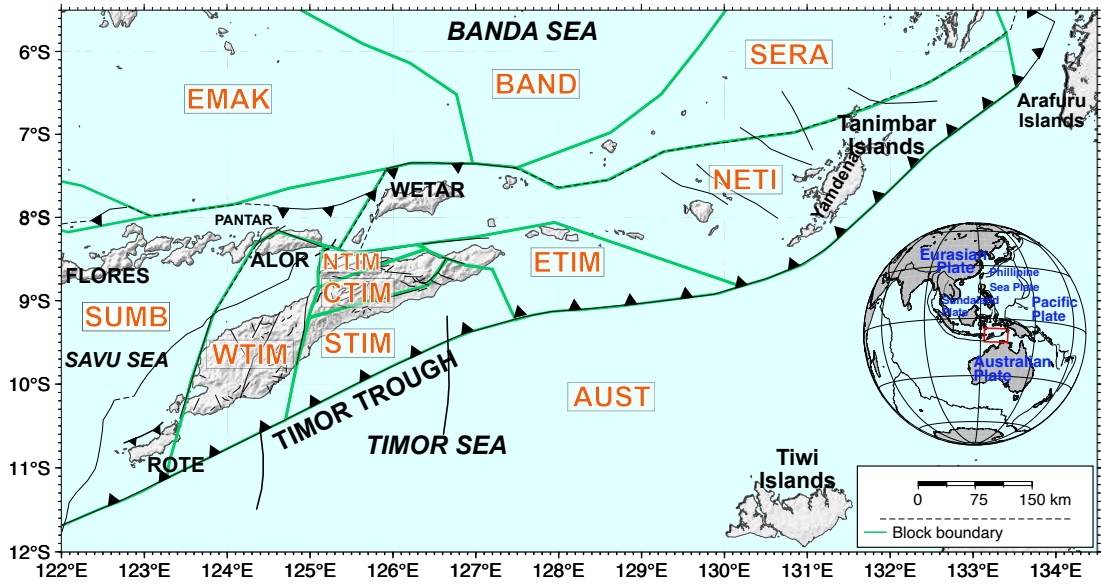


Figure 5.6: Blocks, including the six newly identified Timor micro-blocks— West Timor block (WTIM), Central Timor block (CTIM), North Timor block (NTIM), South Timor block (STIM), East Timor block (ETIM) and North-and-East of Timor block (NETI) blocks, along with the surrounding blocks—Australian Plate (AUST), Sumba block (SUMB), East Makassar block (EMAK), Banda block (BAND) and Seram block (SERA) blocks—as defined by Zhao et al. (2023).

provide a statistically significant improvement in model fit. The null hypothesis is rejected when the calculated F-statistic exceeds the critical value (F_{crit}) at the 95%

confidence level.

Our block model builds on prior studies (Koulali et al., 2016; Zhao et al., 2023) and incorporates the effects of the 2015 Alor earthquake (Figure 5.1). In the western boundary of the Timor Block, we considered the Semaui Fault linked to two mapped faults (Silver et al., 1983; Noya et al., 1997) in the Alor region. First, it connects to a gap that separates Pantar and Alor Island. This fault intersects another fault line trending NE-SW that divides the northwestern peninsula on Alor from the main island. The 2015 Alor earthquake, with M_w 6.2, ruptured along a fault trending NW-SE, which was identified with geodetic data (Funning and Garcia, 2019; Xu et al., 2023). These findings were confirmed by (Nugroho et al., 2024) in which they used a geometric method to identify the fault plane from the auxiliary plane in the focal mechanism of the main earthquake and its largest aftershock (Zahradnik et al., 2008; Mousavi et al., 2023).

We defined **WTIM** as a new block with the Belu Fault as its boundary (No. 7, Figure 5.2). However, lack of **GPS** stations in the western Timor prevents us from considering the Mena-Mana and Turnsip-Toko Faults (No. 8 & 9, Figure 5.2) as potential boundaries, limiting our understanding of their kinematics. Furthermore, these faults are inferred from surface lineaments rather than from direct geological field mapping or seismicity data.

Our fault parameters along the Timor trough and back-arc thrust follow the previous fault modeling of Zhao et al. (2023) in terms of locking depths and dips. Exceptions are in the newly defined block boundaries on Alor Island, which we modeled from our centroid moment tensor solutions (i.e., strike-slip fault) and 10 km locking depth according to the seismogenic zone inferred from foreshocks and aftershocks of the Alor event sequence of the Jiang et al. (2022) catalog. Similarly, we utilized the Banda Arc earthquake catalog (Jiang et al., 2022) to infer the seismogenic depths along the block boundaries in Timor Island. To support our decision in region where distribution of seismicity is insufficient for inferring the locking depth of the faults,

we consider the geology profiles from published literature (Zhao et al., 2025; Kaneko et al., 2007; Charlton et al., 1991; Duffy et al., 2013; Rosidi et al., 1979; Martinez Duran et al., 2020).

5.6 Results and Discussion

Residual horizontal velocities, obtained by subtracting the modeled block motion from the observed GPS velocities, represent the misfit between the model and the observed ground velocities. These residuals along with their associated uncertainties are shown in Figure 5.5. Overall, the residuals are less than 5 mm/yr, except at stations BM27 and ROMA, where larger misfits are observed (~ 7 mm/yr).

The model results can also be evaluated against observed earthquake slip vectors derived from centroid moment tensor solutions. Figure C.4 compares the observed and calculated slip vectors, providing an independent assessment of the modeled block kinematics. The calculated vectors generally reproduce the observed directions, although differences in magnitude and direction are evident at individual locations. These discrepancies may reflect uncertainties in the earthquake slip estimates, local deformation that is not captured by the block model, or the simplification of representing deformation as motion between rigid blocks. The agreement between the observed and calculated slip vectors supports the inferred relative block motions.

Our kinematic modeling results are summarized in Figure 5.6, 5.7, Figure 5.8, Table 5.2, and C.7. The best-fitting microblock boundaries are shown in Figure 5.6. Relative fault slip vectors across active block boundaries are illustrated in Figure 5.7 along with 95% confidence ellipses. The vectors represent hanging wall motion relative to the footwall, with arrow size corresponding to slip magnitude and tails anchored on the hanging wall. For reference, gray vectors and ellipses from a previous study are also shown. Block rotation rates relative to the Australian Plate are indicated by pink wedges, where westward-opening wedges represent anticlockwise rotation; associated uncertainties are shown by navy blue wedges (Table 5.2). Figure 5.8

presents the fault slip rate components, separated into fault-parallel and fault-normal directions. The interseismic coupling coefficients derived from the inversion are discussed below.

The interseismic coupling inversion yields 11 independent coupling-ratio parameters distributed across the modeled fault system. The resulting coupling coefficients show substantial spatial variability, ranging from near-zero values (<0.001) to values approaching unity (~ 0.96 – 1.00), with one intermediate value of ~ 0.48 . The largest uncertainties are associated with coupling parameters located away from the main Timor region, particularly along fault boundaries within the Australian continental plate. These parameters are therefore less well constrained and should be interpreted cautiously. The coupling results indicate spatially heterogeneous interseismic coupling across the modeled fault system rather than uniform locking.

To evaluate whether subdivision of the Timor Block is statistically justified, we compared the single-block and divided-block kinematic models using an F-test (Stein and Gordon, 1984). The single-block model produced a Data χ^2 of $\chi_1^2 = 163.98$, with $k_1 = 4$ estimated parameters, whereas the divided-block model yielded a Data χ^2 of $\chi_1^2 = 106.99$, with $k_2 = 47$ parameters. Both models were evaluated using the same GPS dataset ($N = 298$ velocity components) and identical external block boundaries and fault parameterization; the only additional complexity was the introduction of the internal block boundary. The resulting F-test yielded $F = 3.109$, which exceeds the critical value ($F_{\text{crit}} = 1.429$) at the 95% confidence level ($p < 0.001$). This statistically significant reduction in Data χ^2 indicates that introducing the internal block boundary provides a significantly improved representation of the observed GPS velocities, supporting the interpretation that the Timor region is more appropriately represented by a subdivided block model than by a single rigid block.

The block-model and spherical-wavelet results provide complementary perspectives on deformation in the Banda Arc region. The block model characterizes relative block motions and slip along modeled fault boundaries, whereas the spherical

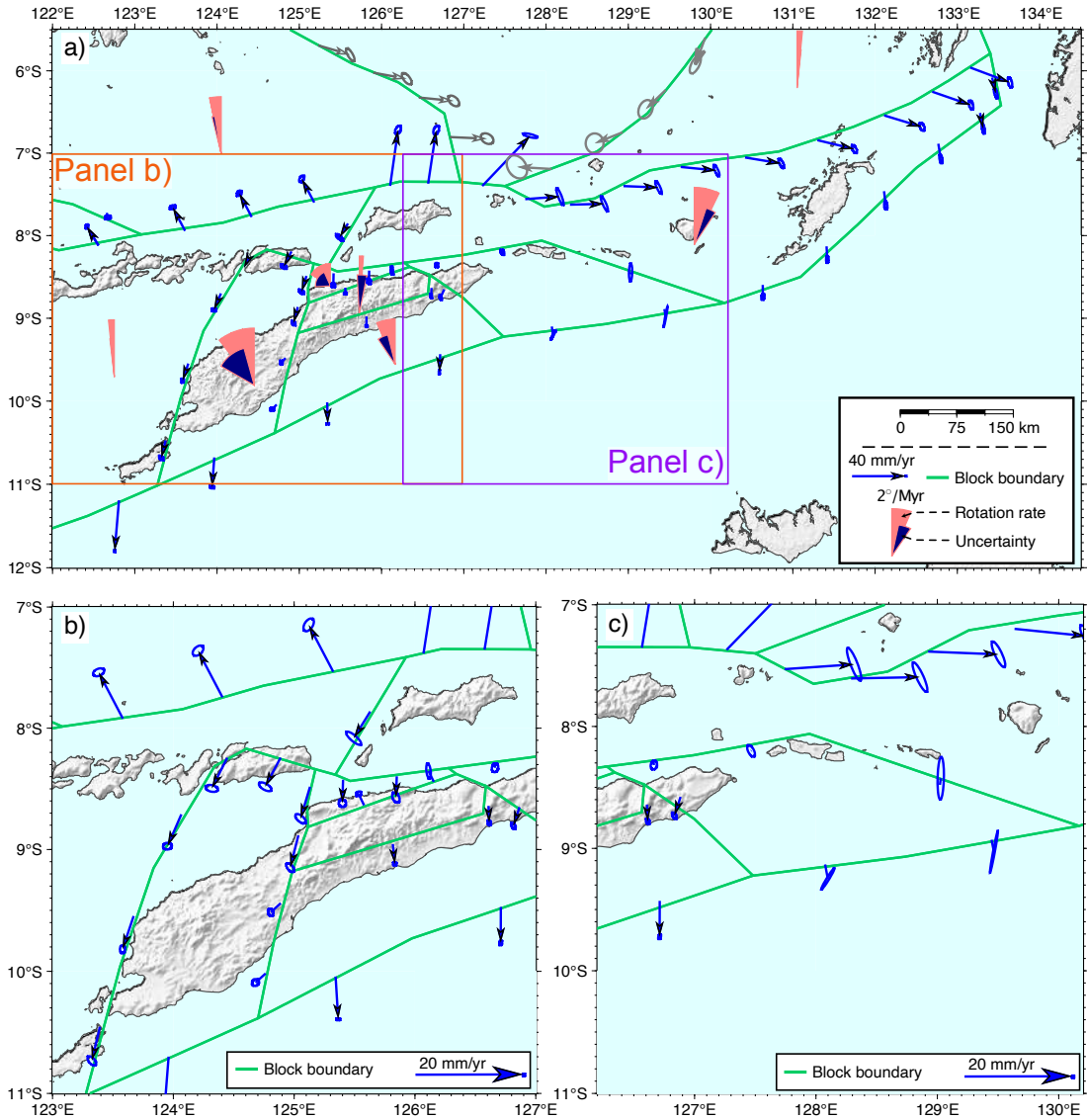


Figure 5.7: (a) Relative fault slip vectors across the active block boundaries with 95% error ellipses. The size of the arrows corresponds to the magnitude of the slip vectors, with arrows showing the movement of the hanging wall relative to the footwall. The arrow tails are positioned on the hanging wall. Gray arrows and ellipses are from a previous study. Pink wedges indicate the block rotation rate relative to the Australian Plate; wedges opening to the west signify anticlockwise rotation, and vice versa. Navy blue wedges represent the uncertainties in the rotation rates. The vector scale is shown in the lower right corner. The bounding boxes for panels (b) and (c) are outlined in orange. (b–c) Fault slip vectors across the active block boundaries with 95% error ellipses, shown for the areas outlined in (a). The vectors are plotted using a reference scale of 20 mm/yr to improve the visualization of lower-rate slip without altering the underlying model results.

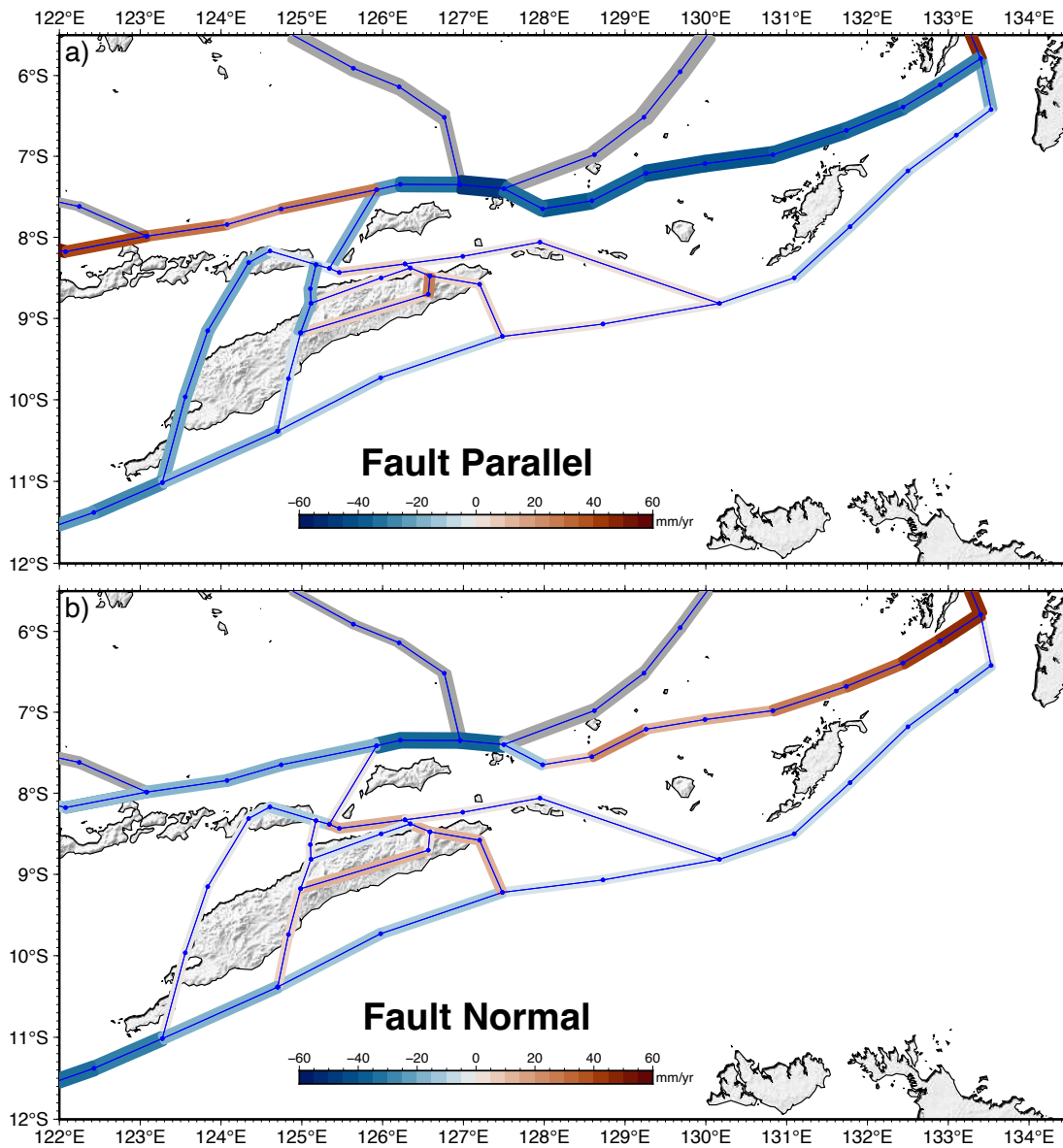


Figure 5.8: Fault slip rate components: (a) Fault-parallel component—positive values (warm colors) indicate right-lateral slip, while negative values (cool colors) signify left-lateral slip. (b) Fault-normal component—positive values (warm colors) indicate extension, while negative values (cool colors) signify compression. In both figures (a & b), the thickness of the colored segments reflects the direction of increasing fault component (see Table C.7 for exact values), and the color intensity corresponds to slip rates, with more intense colors representing higher slip rates. The gray boundaries in both figures are from a previous study.

wavelet method captures the spatial distribution of distributed strain. In this study, the two approaches are interpreted separately, with their results providing qualitative context for understanding the regional deformation pattern rather than constituting a formally integrated or jointly inverted model.

The spherical wavelet method produces a continuous velocity field from the observed GPS velocities after removal of the reference-frame rotation (Figure 5.3(a)). The resulting velocity field represents the spatially continuous, observation-based surface deformation and is independent of the block-model parameterization. The horizontal strain rate derived from this method is displayed in Figure 5.3(b). The results reveal significant strain rates within the NTIM, STIM, and onshore ETIM regions of Timor Island, indicating that deformation is spatially distributed across these regions. These wavelet-derived strain rates describe the observed deformation field and are not residuals obtained after removing the block-model solution.

Our block model (Figure 5.6) indicates that slip rates increase from Flores to the east, peaking in the northern segments of Wetar Island. East of Wetar the rates decrease before rising again towards the end of the NETI block. In the Timor Trough block segments, slip rates increase westward from the ETIM block and rise eastward from the ETIM, though on a smaller scale. Based on slip distribution from our block model (Figure 5.7 & 5.8), energy release between the Timor Trough and the back-arc thrust is primarily accommodated by the Wetar-Atauro, Northern Belu, Alor Island, and Semaui fault segments, with slip rates ranging from approximately 11-13 mm/yr.

Relative to the Australian reference frame, the six newly identified Timor micro-blocks show varying levels of motion. The highest slip rates are observed at the back-arc thrust, indicating significant strain accumulation. In contrast, the central Timor region shows lower slip rates, based on GPS observations spanning the past two decades, suggesting potentially lower levels of seismicity.

The WTIM and NTIM blocks rotate counterclockwise at about $4^\circ/\text{Myr}$, with higher uncertainties due to the limited number of GPS observations. The CTIM

block remains kinematically stable, as indicated by its low rotation rate and the low slip rates along its bounding faults, while the [STIM](#) block rotates counterclockwise at a slower rate. The [ETIM](#) and [NETI](#) blocks, on the other hand, rotate clockwise at about $2^\circ/\text{Myr}$ (Figure 5.7).

The observed counterclockwise rotation in the west, along with the associated left-lateral slip along faults such as the Semau, Northern Belu, and faults on Alor Island (Figure 5.2 & Figure 5.8a), is likely due to shortening in the transitional zone between the ongoing subduction of the Indo-Australian Plate to the west and the collisional front of the Australian continental margin and the Banda Arc in the east. In contrast, clockwise rotation is associated with extension in the southern segments of the [ETIM](#) boundary and increasing extension rates in the northern segments of the [NETI](#) block (Figure 5.8b).

Changes in rotation rates across the blocks may indicate shifts in the regional stress regime. The observed counterclockwise rotation in the west and clockwise rotation in the east may be influenced by the unique geometry of the collisional margin ([Miller et al., 2021](#); [Zhang and Miller, 2021](#); [Keep and Haig, 2010](#)), which results in underthrusting in the western part of the Timor Trough and accretion in the eastern part, as analyzed from multibeam bathymetry and 2D seismic reflection data ([Coudurier-Curveur et al., 2021](#)). This complex tectonic interplay highlights the dynamic nature of the Banda Arc region, where the transition from subduction to collision drives diverse deformation patterns across the micro-blocks.

The distribution of lateral movements in the region is shown in Figure 5.8. In the back-arc thrust segments, right-lateral and left-lateral faulting are divided at the segment between the back-arc thrust and the Wetar-Atauro fault, indicating a combination of interacting tectonic forces and shifts in the dominant stress regimes.

Table 5.2: Summary table of the Euler vectors derived from this study (reference plate: AUST). Lon and Lat represent the position of the relative Euler Pole, ω refers to the rotation rate (positive value represents anticlockwise rotation), $\sigma\omega$ refers to the standard error of our estimated rotation rate; E_{max} and E_{min} are the maximum and the minimum axis of longitude/latitude error ellipses, respectively.

Plate (Block name/Ref. Block name)	Lon (deg)	Lat (deg)	ω °/Myr	$\sigma\omega$ °/Myr	E_{max} (deg)	E_{min} (deg)
ETIM/AUST	136.5644	-7.4033	4.308	1.400	2.62	0.29
SERA/AUST	133.5462	-24.6691	0.746	0.251	2.34	0.25
SUMB/AUST	135.2015	-11.8887	-0.036	0.038	0.36	0.08
WTIM/AUST	136.3262	-11.3572	-4.567	1.120	2.81	0.29
CTIM/AUST	144.6302	-12.5292	0.199	0.365	1.94	0.54
NTIM/AUST	139.7189	-8.1821	-5.090	1.728	2.68	0.46
STIM/AUST	133.8950	-9.3760	-2.400	0.501	1.44	0.16
NETI/AUST	122.1973	-8.7232	2.209	0.384	1.41	0.57
EMAK/AUST	141.3833	-8.7738	-0.504	0.102	2.54	0.28
BAND/AUST	80.6687	26.9112	-5.174	0.245	3.37	0.28

Compression rates increase westward along the Timor Trough segments, consistent with the ongoing convergence and subduction of the Indo-Australian Plate beneath the Banda Arc. In contrast, the highest modeled extension rates occur toward the eastern end of the back-arc, near the boundary with the [NETI](#) block. This extension is instead likely related to the complex relative motions among the Australian Plate, Sunda Block, and Philippine Sea Plate, potentially modulated by eastward rollback of the Banda slab. Given the limited evidence for significant deformation from seismic imaging in this region, however, the modeled extension should be interpreted cautiously and does not necessarily imply widespread extensional faulting across the back-arc.

5.6.1 Strain Accumulation, Slip Rates and Seismic Hazards

The highest strain accumulation is observed in the deformation zone extending from Dili to the Lacle Fault ($\sim 2.15 \times 10^{-7}/\text{yr}$, with the Baucau Fault and its nearby areas showing slightly lower strain rates ($\sim 1.50 - 2.00 \times 10^{-7}/\text{yr}$). Other faults, except for the Mata Bia Fault, exhibit strain rates of up to $\sim 1.15 \times 10^{-7}/\text{yr}$. In contrast, central Timor and the Mata Bia Fault show notably low strain rates, below $0.30 \times 10^{-7}/\text{yr}$, suggesting limited resolvable current deformation in these areas. However, low strain rates do not necessarily imply low seismic hazard, as slowly accumulating strain may still be released during future earthquakes. In West Timor, the deformation zones also display low strain rates, but the sparse [GPS](#) observations in this region may limit our ability to resolve localized deformation and could therefore result in an underestimation of the actual strain accumulation.

A similar limitation applies to the interpretation of the block-model results on Alor Island. preferred block model assigns a slip rate of ~ 10 mm/yr to the Fault 11 on the Alor Island (Figure 5.2; hereafter, the Alor Fault). This value should be interpreted with caution because the available [GPS](#) observations in the Alor region are sparse. The opposing strike-slip rates associated with the Alor Fault may reflect localized deformation, but may also result from the limited ability of the available observations to resolve the detailed block geometry and partitioning of deformation. In particular, the present [GPS](#) coverage is insufficient to determine whether the fault represents a major block boundary or whether the observed deformation is distributed across a broader region. Thus, both the low strain rates inferred in data-sparse regions and the relatively high slip rate assigned to the fault should be considered in the context of the observational limitations. More comprehensive geodetic and seismic observations across West Timor and Alor are needed to better resolve strain accumulation, block geometry, and fault slip rates and to improve assessment of the spatial distribution of seismic hazard in these regions.

The seismicity provides some evidence for active deformation in and around Alor

(Figure 5.1, but does not independently establish the activity or slip rate of the Alor Fault. Earthquakes occur in the vicinity of the mapped fault system; however, the association of individual events with a specific fault is uncertain because many historical and teleseismic earthquake locations have limited spatial resolution. Prior to the deployment of the local YS seismic network used by Jiang et al. (2022), high-resolution local and regional seismic observations capable of resolving fault-related earthquake sequences were also limited. In addition, the geological interpretation of the structure is based in part on the lineament identified by Silver et al. (1983), for which independent evidence for its activity and kinematics remains limited.

Therefore, the ~ 10 mm/yr slip rate obtained for the Alor Fault should be regarded as a model-dependent estimate rather than a uniquely determined slip rate. Alternative block geometries, including configurations in which the fault is or is not treated as a block boundary, could produce different slip-rate estimates and should be evaluated as additional geodetic and seismic observations become available. We therefore do not interpret the current result as definitive evidence that the Alor Fault accommodates deformation at ~ 10 mm/yr.

Similar to the finding of Koulali et al. (2016) and Zhao et al. (2023), our block model reveals significant seismic hazards in the region, particularly in the back-arc thrust segments of northern Wetar Island, where the highest slip rates are observed (Figures 5.7 and 5.8). These elevated slip rates correspond to increased strain rates, indicating a substantial accumulation of tectonic stress that could lead to intense seismic activity.

As shown in Figures 5.7 and 5.8, the coexistence of both high parallel slip ($\sim 32.03 \pm 2.22$ mm/yr) and high normal slip ($\sim 39.75 \pm 0.57$ mm/yr) suggests the presence of oblique-slip faulting, accommodating significant horizontal and vertical movements (~ 51 mm/yr). This dual strain accommodation can reduce the buildup of stress in a single direction but may result in more complex earthquake patterns, posing challenges for seismic hazard assessment.

The distribution of segments undergoing extension and compression is shown in Figure 5.8. The highest compression rates, combined with high slip rates of left-lateral movement, are concentrated in the back-arc segments north of Wetar. This stress accumulation, along with lateral movement, is strongly associated with a higher seismic risk in these areas, as indicated by several large-magnitude earthquakes that have occurred in this region in recent years (Figure 5.1a).

5.6.2 Tectonic Implications

The observed block rotations vary systematically along the Timor margin, with counterclockwise rotations of approximately $2\text{--}4^\circ$ in western Timor and clockwise rotations of approximately 2° in the east (Figure 5.7). This spatial variation suggests that the observed deformation is likely influenced by multiple interacting processes rather than a single regional driving mechanism. The inherited structural framework of the forearc, established during its earlier evolution along the Sunda margin, may influence the way deformation is accommodated along the margin. In addition, eastward rollback of the Banda slab provides a regional tectonic setting that may promote along-arc motion and extrusion of the forearc. This motion is likely further modified by the progressive collision and indentation of the Australian continental margin, which is heterogeneous in both structure and composition along strike. Deformation within the accretionary prism, including gravitational processes, and the development of back-arc thrusting may provide additional mechanisms for accommodating convergence. Along-strike variations in the geometry and structure of the subducting slab, as indicated by seismic tomography, may further contribute to the spatial variation in deformation.

The differential rotation is also consistent with lateral motion of the NTIM and STIM blocks relative to the CTIM block, suggesting that deformation is accommodated, at least in part, along fault systems extending from Dili to Laclo in the north and along the southern fault zone toward the Viqueque Fault. The concentration

of high strain rates within these blocks (Figure 5.3) further indicates that active deformation is localized within these regions. In particular, the modeled right-lateral and slightly extensional kinematics of the Lacle Fault are consistent with previous interpretations of combined strike-slip and extensional deformation along structures in southern Timor (e.g. Duffy et al., 2013). These results suggest that the Lacle Fault currently accommodates oblique deformation and may represent the reactivation of inherited structures during the ongoing tectonic evolution of the Banda Arc.

The transition from counterclockwise to clockwise block rotations, the differential motion between the NTIM, CTIM, and STIM blocks, and the concentration of strain along specific fault systems suggest that deformation is strongly partitioned across the Timor margin. In this framework, the observed rotation pattern may reflect spatial variations in the relative contribution of forearc motion, continental indentation, accretionary-prism deformation, and back-arc faulting. Although the available kinematic data cannot uniquely resolve the contribution of each mechanism, their combined effects provide a plausible framework for explaining the observed pattern of forearc deformation.

The transmission of crustal deformation from the Timor Trough to the back-arc thrust is accommodated not only by the Semaui Fault, as indicated by previous study (Koulali et al., 2016) on the Timor Block, but also by the northern segment of the Belu Fault. Seismicity along the fault zones observed in recent years further supports their role in accommodating deformation in the region (Jiang et al., 2022).

The relatively large extension modeled across the Wetar Suture warrants caution given the limited deformation identified by seismic imaging. The modeled extension is spatially heterogeneous, with the largest values concentrated along the western segment of the Wetar Suture, where rates locally exceed $>\sim 10$ mm/yr, whereas the eastern segment shows substantially lower rates of approximately 0–5 mm/yr (Fig. 5.8b). The relative motion of the NTIM block with respect to the NETI block, particularly constrained by observations on Wetar Island, is consistent with this dif-

ferential deformation. However, the magnitude of the modeled extension does not necessarily imply widespread extensional reactivation of the Wetar Suture. Some of the modeled relative motion may instead be distributed across multiple structures or accommodated by deformation that is not resolved by existing seismic imaging (Masson et al., 1991). Further geological and geophysical observations are required to determine whether the modeled extension corresponds to active extensional faulting and to better constrain its structural expression.

The newly identified fault on Alor accommodates predominantly right-lateral motion, with only minor compression strain observed at ~ 10 mm/yr from the GPS-derived strain and block model results (Fig. 5.8). This is consistent with a dominantly strike-slip regime in the seismogenic depth range, where the moment tensor indicates pure strike-slip (Nugroho et al., 2024), while shallow transpressional effects produce minor surface shortening.

5.7 Conclusions

Using GPS data from 2018 and 2019, along with unpublished data from 2005 and 2014, we refine the Timor Block using a total of 37 stations from Timor-Leste, including data from the DILI semi-permanent station and permanent stations from BIG and IGS (Figure 5.4; Table C.5). We redefine boundaries between the Sumba Block and West Timor, considering the M_w 6.5 2015 Alor earthquake. These proposed microplate boundaries satisfy constraints from existing fault maps (Figure 5.1a, b & Figure 5.2) and regional seismicity, including historical and instrumental seismic records, and marine geophysical survey data. We further constrain the deformation patterns using the spherical wavelet method to generate continuous surface velocity and horizontal strain rates.

Our findings provide a more comprehensive understanding of deformation patterns in the Banda Arc region. The results reveal more detailed tectonic motions, with the fastest velocities occurring at approximately 53 mm/yr from Flores to northern

Wetar. This includes components of left-lateral strike-slip in the Timor Trough, shortening north of Wetar due to plate convergence, and extension at the eastern boundary with the [NETI](#) block. Additionally, we observe changes in rotation velocities, with counterclockwise rotation in the west and clockwise rotation in the east, likely driven by the irregular geometry of the collisional margin.

5.8 Data and Resources

In the supplementary materials, we provide [GPS](#) velocities and calculated slip vectors used in this study. Raw [GPS](#) data are archived by the [UNAVCO](#) and can be requested from the [UNAVCO](#) portal (<https://www.unavco.org/data/gps-gnss/data-access-methods/dail/campaign.php>). The control and input files for the modeling we performed in this study are available in the Supporting Information.

5.9 Acknowledgments

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Conclusion and future study

Our study set out to investigate the complex tectonic setting of the Indonesia–Australia–New Guinea region, with particular focus on the western Banda Arc and the internal deformation of the Timor block. Several interrelated research questions guided our work, including: What is the current state of plate boundary reorganization in the region, considering the growing number of proposed microplate boundaries? How is deformation expressed in the Timor block, and what do [GPS](#) and seismic data reveal about its internal dynamics? What role does the Timor Trough play in accommodating convergence?

6.1 Regional-Scale Plate Boundary Reorganization

This thesis provides a broad-scale quantitative framework for understanding the ongoing reorganization of the Indonesia–Australia–New Guinea plate boundary, with particular emphasis on the young collisional complex of the western Banda Arc. As part of this effort, we developed the first region-wide kinematic block model for the [IANGCZ](#) collision zone by integrating more than 200 [GPS](#) observations and 492 earthquake focal mechanism slip vectors from across the Banda Arc and surrounding regions. The resulting [GPS](#)-based kinematic model captures broad plate motions and fills important gaps in our understanding of deformation across the Banda Sea and West New Guinea regions.

Present-day [GPS](#) kinematics provide a snapshot of the ongoing reorganization

of the Banda Arc, but they do not by themselves permit a quantitative reconstruction of its evolution over the past 3 Myr. The spatial variation in deformation from Flores and Alor to Wetar, particularly the stronger shortening around Flores–Alor compared with the reduced shortening and more oblique deformation toward Wetar, may reflect changes in the way convergence has been accommodated along the arc. Geological and marine geophysical observations provide evidence that these spatial variations developed over longer timescales. [Silver et al. \(1983\)](#) documented substantially greater shortening near Alor than near Wetar, while observations of seafloor faulting by [Masson et al. \(1991\)](#) provide evidence for continued offshore deformation. Seismic tomography ([Supendi et al., 2020a](#)) further indicates along-arc variations in the structure of the subducting and colliding lithosphere. Together with the seismic observations from the Alor earthquake sequence, these independent constraints suggest that the present-day deformation field represents an ongoing stage of structural reorganization of the Banda Arc rather than a uniform continuation of convergence.

The observed clockwise rotation of the eastern Timor blocks and the oblique deformation around Alor–Wetar further indicate that convergence is accommodated differently along the eastern Banda Arc. However, quantitatively reconstructing the changes required to produce the present-day configuration over the last 3 Myr would require additional constraints on the timing and rates of fault development, past plate motions, and the evolution of crustal and lithospheric structure. Such a reconstruction is beyond the scope of this study. Instead, our [GPS](#)-derived kinematics provide constraints on the modern stage of this longer-term tectonic reorganization and provide a framework for future investigation integrating geodetic, seismic, tomographic, and marine geological observations.

More broadly, the results demonstrate that plate boundary deformation is accommodated through the interaction of multiple rotating and translating tectonic blocks rather than along a single continuous deformation front. Significant variations in

fault slip rates, convergence patterns, and block rotations reveal pronounced spatial changes in deformation style and strain partitioning along the plate boundary. In western New Guinea, the model indicates that the evolution of the Cenderawasih Bay region is associated with the combined effects of Bird's Head block rotation and southwestward motion of the Weyland Overthrust, as reflected by variations in convergence partitioning and fault slip behavior. Elevated model residuals in some regions further suggest the presence of unresolved internal deformation or unmodeled micro-blocks, highlighting the complexity of ongoing plate boundary reorganization (Chapter 4).

In summary, this thesis demonstrates that deformation within the Indonesia–Australia–New Guinea region is characterized by distributed strain accommodation, complex block interactions, and spatially variable deformation along major active structures. The present-day kinematic framework provides a basis for evaluating how these deformation patterns relate to the longer-term reorganization of the Banda Arc.

6.2 Internal Deformation of the Timor Block

The internal deformation of the Timor Block is investigated through an expanded regional GPS velocity field and a refined kinematic block model. Although the Timor Block exhibits a relatively low reduced (X^2_{red}) value, indicating a satisfactory fit to the GPS velocities at the block scale (presented in the Chapter 4), further analysis demonstrates that it cannot be fully represented as a single rigid body. The limited spatial density of GPS observations in the region also highlights the challenges in resolving deformation at finer scales within the block. By combining GPS observations, block modeling, and wavelet-based multiscale strain analysis (Chapter 5), this study reveals that Timor Island undergoes significant internal deformation.

The refined model identifies six kinematic micro-blocks within the Timor region, bounded by active faults and localized deformation zones. These micro-blocks accommodate distributed strain, as indicated by the spatial patterns of velocity fields

(Figure 5.5), relative fault slip vectors (Figure 5.7), and fault slip rate components (Figure 5.8). The incorporation of the newly identified fault on Alor Island as a block boundary further supports the presence of active internal segmentation and demonstrates that deformation within the Timor region is partitioned across multiple fault-bounded domains. These results challenge simplified representations of the Timor Block as a monolithic unit and support a more dynamic view of crustal partitioning and distributed convergence within the Banda Arc.

Using observations from Timor-Leste and surrounding regions, this study further refines the boundaries between the Sumba Block, West Timor, and adjacent blocks by incorporating geodetic velocities, regional seismicity, mapped faults, and marine geophysical constraints. The deformation field reveals high velocities of up to ~ 53 mm/yr from Flores to northern Wetar, left-lateral strike-slip deformation along the Timor Trough, shortening north of Wetar associated with plate convergence, and extension along the eastern boundary with the [NETI](#) block. Spatial variations in block rotation, including counterclockwise rotation in the west and clockwise rotation in the east, are consistent with the influence of the irregular geometry of the collisional margin on regional deformation.

6.3 Contribution of Seismic Data

While [GPS](#) observations provide constraints on interseismic crustal deformation and block kinematics, seismic data provide complementary insights into transient strain release and fault rupture processes. The integration of [GPS](#)-derived deformation patterns and earthquake source analyses reveals that deformation in the Timor–Banda region is accommodated through a combination of block motion, fault slip partitioning, and transient earthquake-related deformation processes.

Seismic data collected from a temporary array of 30 broadband instruments—deployed across the Banda Arc region as part of the YS network ([Miller et al., 2016](#))—played a crucial role in refining our understanding of earthquake source

mechanisms, active fault structures, and local deformation processes. Our approach involved computing nine Centroid Moment Tensor (CMT) solutions to characterize the source mechanism of the 2015 Alor earthquake sequence. To evaluate the stability of centroid locations and nodal planes, we utilized a range of frequency bands during full waveform modeling and considered various 1D velocity models. Additionally, we determined the hypocentre, fault plane, and rupture direction for the largest foreshock and main event, identifying the fault plane by examining geometric relationships between the hypocentre and nodal plane centroids derived from the CMT solutions. This detailed source analysis of the 2015 Alor earthquake sequence—including CMT inversion, hypocenter relocation, fault plane identification, and rupture pattern interpretation—led to the recognition of a previously unidentified fault on Alor Island (Chapter 3). The fault is now interpreted as an active structure that contributes to regional strain accommodation. This newly identified fault was incorporated as a block boundary in subsequent geodetic modeling (Chapter 5), allowing us to better assess its role within the broader crustal deformation system in the western Banda Arc.

6.4 Outcomes of the thesis

The outcomes of this thesis contribute to a more comprehensive understanding of regional tectonics by integrating CMT inversion, GPS-based block modeling, and wavelet-based strain analysis. This multi-scale approach enables improved characterization of plate and microplate interactions, internal block deformation, and active fault structures in the Indonesia–Australia–New Guinea collision zone.

In Chapter 3, we utilized data from a temporary seismic deployment to describe the source mechanism, rupture direction, and rupture pattern of the 2015 Alor earthquake. These data were critical in constructing a local Earth 1D velocity model, which enable accurate estimates of both hypocentre and centroid source location.

In Chapter 4, we demonstrated that large-scale block models can be constructed

using [GPS](#) data to understand the interaction between tectonic blocks in the region.

Building on this work, our study in Chapter 5 introduced characterisation of fault slip rates and seismic potential derived from large-scale block models. This was achieved by delineating the Timor block into six micro-blocks, highlighting ongoing deformation and seismic potential. We also incorporated the Alor Island fault as a new boundary for block delineation, confirmed through source mechanism analysis using centroid moment tensor inversion. Furthermore, we generate a continuous, multiscale analysis from the discrete [GPS](#) observation data using the spherical wavelet method to provide a distributed deformation patterns in the region.

Our research highlights the importance of integrating geodetic and seismic data to advance the understanding of active tectonic processes in the Banda Arc region. In particular:

- Temporary seismic deployments are essential for in-depth source studies, enabling the construction of local Earth 1D models.
- The integration of [GPS](#) data from campaign sites with high-frequency measurements can provide valuable insights into slow deformation patterns.
- Permanent or semi-permanent [GPS](#) stations offer significantly better data for describing long-term subsurface deformation than short-duration campaign data. For example, while permanent stations typically achieve velocity uncertainties of less than 1 mm/yr over several years of continuous data, campaign data—especially from sites visited only once every few years—can result in uncertainties exceeding 2–3 mm/yr, limiting their ability to detect subtle deformation signals or resolve low strain-rate gradients.

6.5 Prospective Future Work

The lack of [GPS](#) data in the West Timor block currently limits our ability to resolve deformation within the region bounded by the Mena-Mana and Turnip-Toko Faults

(Figure 5.2). This data limitation also restricts our ability to characterize the deformation pattern in the northeastern and southwestern regions of Alor Island, which are separated by a fault investigated in Chapter 3, and to assess its kinematic relationship with West Timor. Consequently, it remains unclear whether this region can be adequately represented as a single rigid block or whether it comprises multiple blocks separated by these faults. In particular, an alternative geometry incorporating the Rote–Alor fault as a block boundary is geologically plausible and warrants further testing. Because this alternative geometry was not evaluated in the present inversion, we do not consider the adopted block configuration to be uniquely determined. Rather, the current geometry represents a compromise between geological plausibility and the ability of the available GPS observations to resolve additional model parameters. Future expansion of multi-constellation GNSS campaign surveys across West Timor, Rote, and Alor Island would substantially improve spatial data coverage and provide stronger constraints on alternative block configurations, block boundaries, internal deformation, and strain partitioning. The western Timor–Rote–Alor region therefore represents an important target for future geodetic observations and testing of the robustness of the inferred kinematics.

In addition, the densification of continuous and campaign GNSS observations across northern and eastern Timor, as well as the Banda Sea region, will substantially strengthen the geodetic framework in areas that are currently sparsely instrumented. Improved station density will enhance the resolution of crustal velocity fields and provide stronger constraints on active deformation associated with the Timor Trough, Wetar Back-Arc Thrust, and adjacent fault systems. These expanded observations will improve kinematic block models by reducing uncertainties in estimates of block motions, strain partitioning, fault slip rates, and locking along major plate-boundary faults across the Timor–Banda region.

Complementary to improved geodetic coverage, systematic compilation of mapped fault geometries and slip data from field observations, InSAR, and GNSS coseismic

measurements would enhance regional tectonic interpretation and provide a valuable long-term dataset. Particular emphasis should be placed on improving the characterization of offshore fault systems, including the Wetar Suture and other submarine structures in the Banda Arc, where fault geometries and kinematics remain comparatively poorly constrained. Integrating marine geophysical observations with geodetic and geological datasets would help resolve the continuity, segmentation, and activity of these offshore faults. Future field studies and geological mapping could also identify and date offset geological or geomorphic features, providing independent constraints on fault slip polarity and long-term slip rates. Such observations would help validate the modeled fault kinematics and improve constraints on the timing, magnitude, and spatial variability of fault slip, thereby refining our understanding of active deformation and seismic hazard assessment.

Continued [GNSS](#) observations will also enable improved quantification of post-seismic deformation following the Alor earthquake sequence, including the temporal evolution of afterslip and any associated viscoelastic relaxation. These observations will help distinguish transient postseismic deformation from long-term tectonic motion, leading to more reliable estimates of interseismic strain accumulation and fault slip rates.

The seismic source analysis and [GNSS](#) block models can be extended to other regions within the Banda Arc or other tectonically active areas. This methodology could be applied to study the North and East Timor blocks, with a specific focus on regions like the Tanimbar Islands.

The integrated seismic source analysis and [GNSS](#) block modelling framework developed in this study can be extended to other segments of the Banda Arc and comparable convergent plate boundary systems with a specific focus on regions like the Tanimbar Islands where deformation associated with the Australia–Banda collision remains incompletely resolved.

Despite the high computational demands, computing Centroid Moment Tensor

(CMT) inversion using a 3D Earth model has become common practice. Our method of source mechanism study could alternatively use the 3D Earth model, which offers significant advantages over a 1D model due to its ability to capture the complexities and heterogeneities of the Earth's structure. A 3D model can accurately represent lateral variations in seismic velocities, density, and anisotropy, which is crucial for regions with complex geological features, such as the Banda collisional complex.

The enhanced accuracy of 3D models helps reduce systematic errors introduced by 1D models, which assume horizontally layered structures and often fail to account for lateral variations. By providing a more realistic representation of the subsurface, 3D models improve the resolution of source parameters, such as fault orientation, slip distribution, and rupture processes.

Furthermore, 3D models are capable of incorporating surface topography and oceanic bathymetry, which significantly affect seismic wave propagation, especially in coastal and oceanic regions. This capability is not present in 1D models, making 3D models more suitable for these areas. Furthermore, the ability of 3D models to accurately model higher frequency waveforms enhances their sensitivity to small-scale heterogeneities in the Earth's crust and mantle. This leads to more detailed and precise seismic source characterizations, offering a comprehensive and accurate understanding of the Earth's structure.

Future research should prioritize the joint inversion of InSAR, GNSS, and seismic observations to more robustly constrain the geometry, depth, and kinematics of active deformation sources in the Banda Arc region. In this framework, InSAR provides dense spatial coverage of surface displacement, GNSS contributes high temporal resolution and long-term velocity constraints, and seismic data (including CMT solutions) offer depth-sensitive information on fault geometry and slip processes. When combined with strain-rate estimation approaches such as Vertical Derivatives of Horizontal Stress (VDoHS) (Haines et al., 2015) applied to increasingly dense GNSS networks, this integrated strategy enables improved characterization of both the spatial

distribution and temporal evolution of deformation.

The application of [InSAR](#) in the Banda Arc has historically been limited by tropical environmental conditions, including dense vegetation, rapid land-cover change, steep topography, and strong atmospheric variability, all of which lead to interferometric decorrelation and reduced phase coherence. However, the recent launch of the NASA–ISRO Synthetic Aperture Radar ([NISAR](#)) will significantly mitigate these challenges. [NISAR](#)'s systematic, high-repeat acquisitions and dual-frequency capability (particularly the longer L-band wavelength) will improve coherence in vegetated regions, facilitate the mitigation of atmospheric artifacts, and enable more reliable time-series analysis of subtle ground deformation (e.g., [Qu et al., 2023](#); [Murray et al., 2021](#); [Jiang and Lohman, 2021](#); [Duncanson et al., 2020](#)). When combined with an expanded [GNSS](#) coverage, this will allow more continuous and spatially comprehensive monitoring across previously challenging regions.

Also, incorporating high-resolution Light Detection and Ranging ([LiDAR](#)) data will further enhance deformation studies by providing precise topographic information and resolving fine-scale geomorphic expressions of active faulting. The combined use of [InSAR](#) (including [NISAR](#)), [GNSS](#), seismic datasets, strain-rate mapping, and LiDAR thus offers a comprehensive, multi-scale observational framework. This integrated approach not only improves constraints on deformation processes, fault geometry, and surface expressions, thereby advancing our understanding of complex tectonic processes and strengthening future seismic hazard assessments in the Banda Arc.

The long-term goal of this research is to advance a comprehensive understanding of plate boundary dynamics and to strengthen seismic hazard assessment in earthquake-prone regions. By characterizing deformation patterns and their spatial distribution, we can more accurately quantify seismic hazards and provide critical insights for mitigating earthquake risks. Ultimately, this will contribute to the development of more effective disaster mitigation strategies.

Beyond refining our understanding of specific regions like the Banda Arc, this research aims to enhance global knowledge of plate boundary dynamics. Studying diverse regions with varying tectonic settings will enable us to identify patterns and trends that inform our understanding of how plates interact at their boundaries.

Achieving these goals requires fostering interdisciplinary collaboration between earth scientists and experts from various fields. By working together, we can develop new methodologies and tools that integrate diverse data sets and illuminate the complexities of crustal deformation related to plate boundary dynamics.

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Appendix A: Supplementary Materials of Rupture pattern of 2015 Alor earthquake sequence, Indonesia

Supplementary Materials

Rupture pattern of 2015 Alor earthquake sequence, Indonesia

H. Nugroho, B. Hejrani, S. Mousavi, M. S. Miller

This supplementary document contains ten supplementary figures for the manuscript titled “Rupture pattern of 2015 Alor earthquake sequence, Indonesia.”

Figures in this document: [A.1](#), [A.2](#), [A.3](#), [A.4](#), [A.5](#), [A.6](#), [A.7](#), [A.8](#), [A.9](#), [A.10](#).

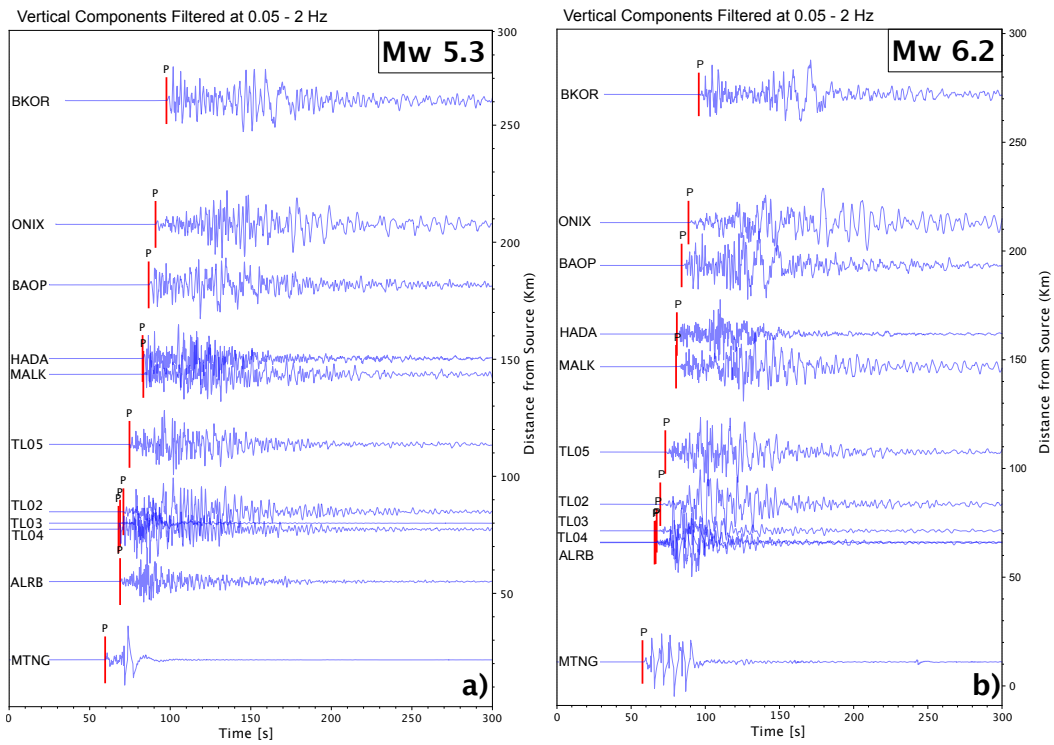


Figure A.1: P-wave arrivals picked in study are overlaid with a red line on the waveforms from the vertical components of the YS network for (a) the largest foreshock M_w 5.3 occurred on November 3 and (b) the mainshock M_w 6.2 occurred on November 4, 2015. Station names are labelled on the left.

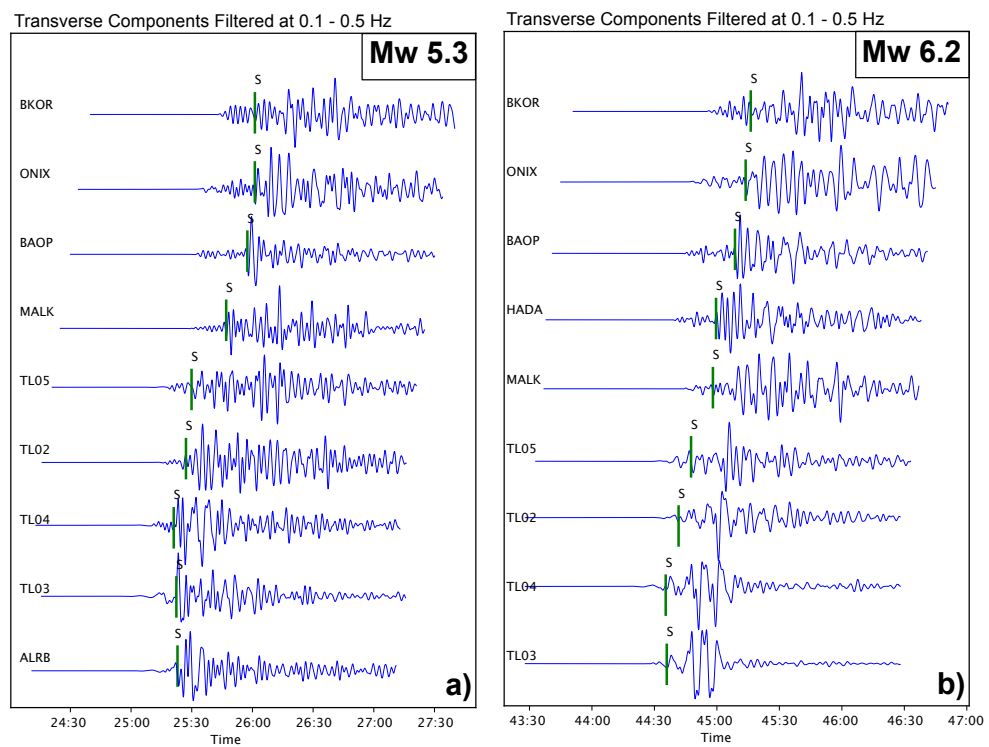


Figure A.2: Same as Fig. A.1, but for S-wave arrivals (green line) on the transverse component.

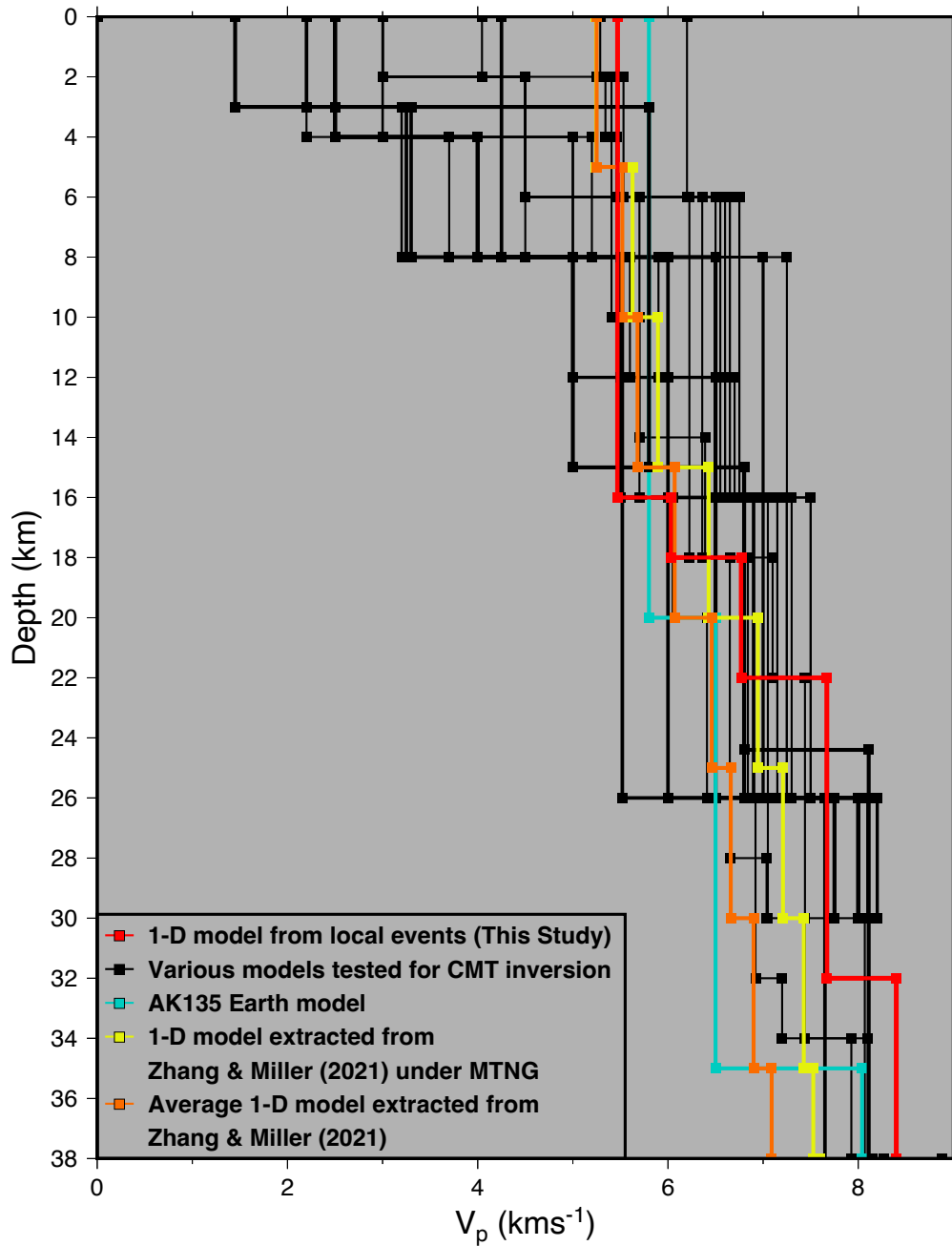


Figure A.3: The 1-D Earth models tested in this study in CMT and hypocenter inversion. The red model derived from local earthquake data under the YS network provides the highest fit to the waveform data in CMT inversion. A range of other models (shown in black) derived from active seismic studies (e.g., Shulgin et al., 2009) and Ak135 did not improve the fit to waveform data. Two local 1D models extracted from the 3D ambient noise tomography model by Zhang and Miller (2021) were tested for hypocenter location as well as Ak135 (Fig. 3.4)

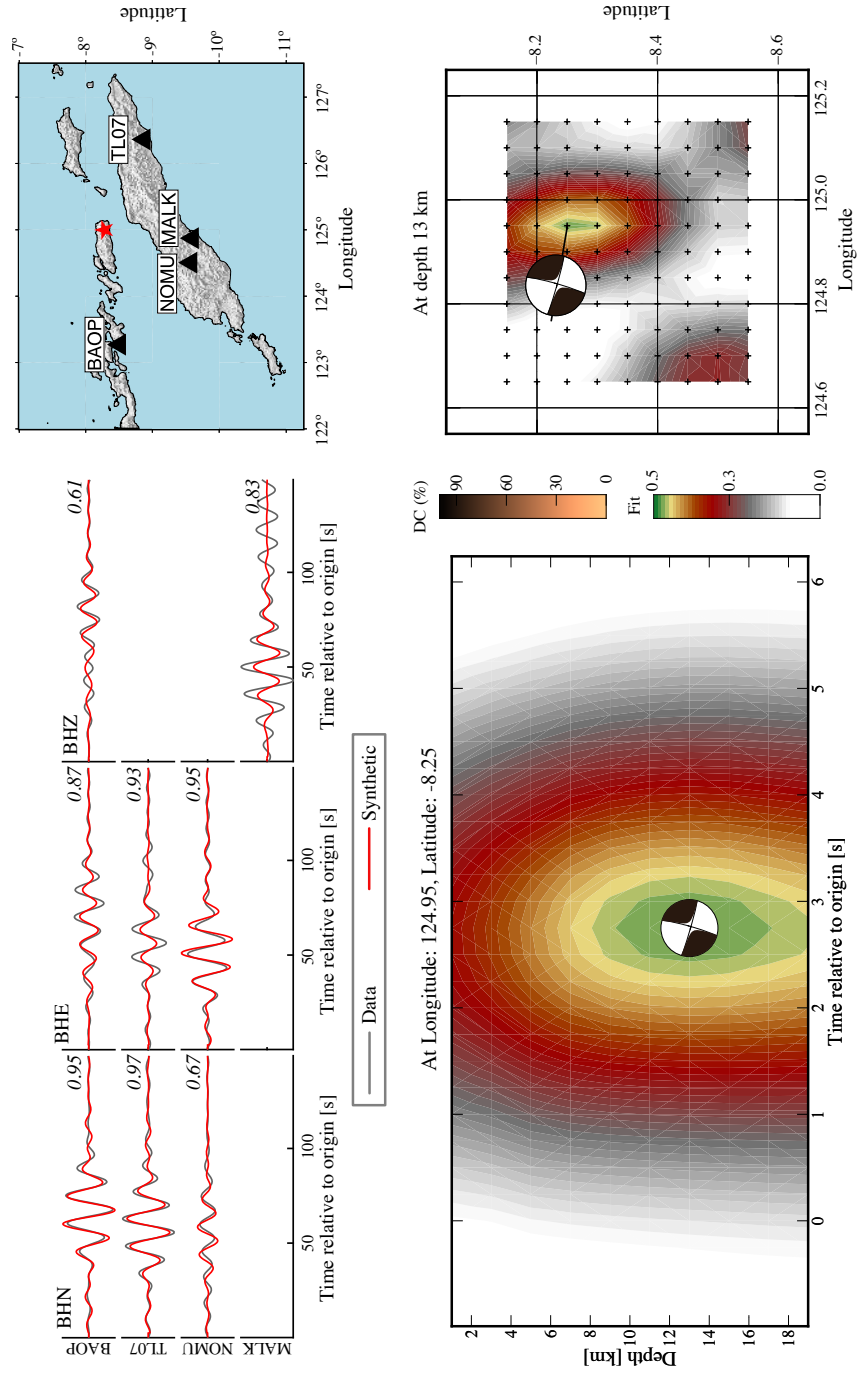


Figure A.4: Result of CMT inversion for the M_w 4.0 Foreshock (F1) event occurred on 2015-11-01. The waveforms, the stations, and the two diagrams are plotted similar to Figs. 3.2 and 3.3.

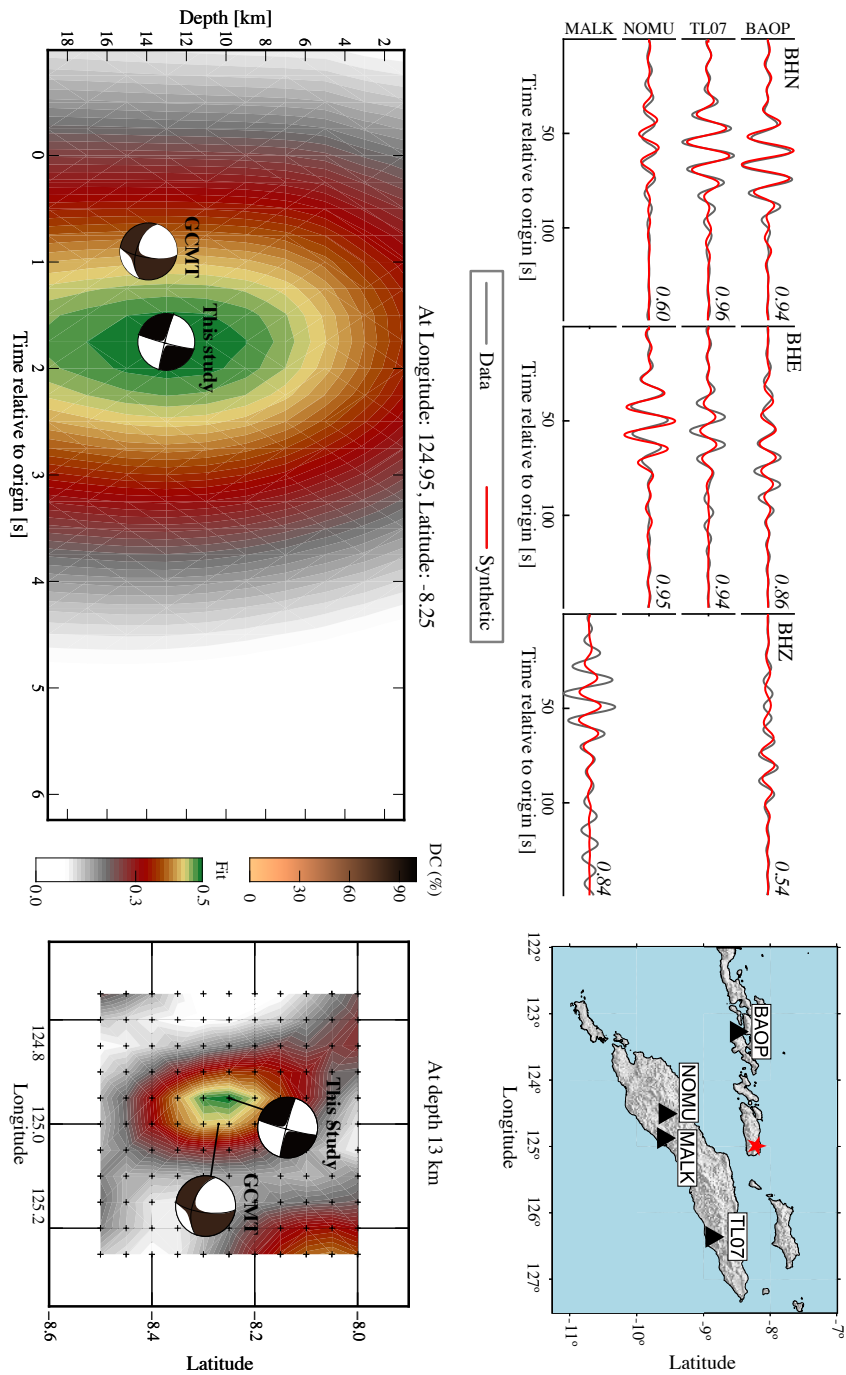


Figure A.5: Same as Fig. A.4 but for the M_w 4.57 Foreshock (F2) event occurred on 2015-11-03.

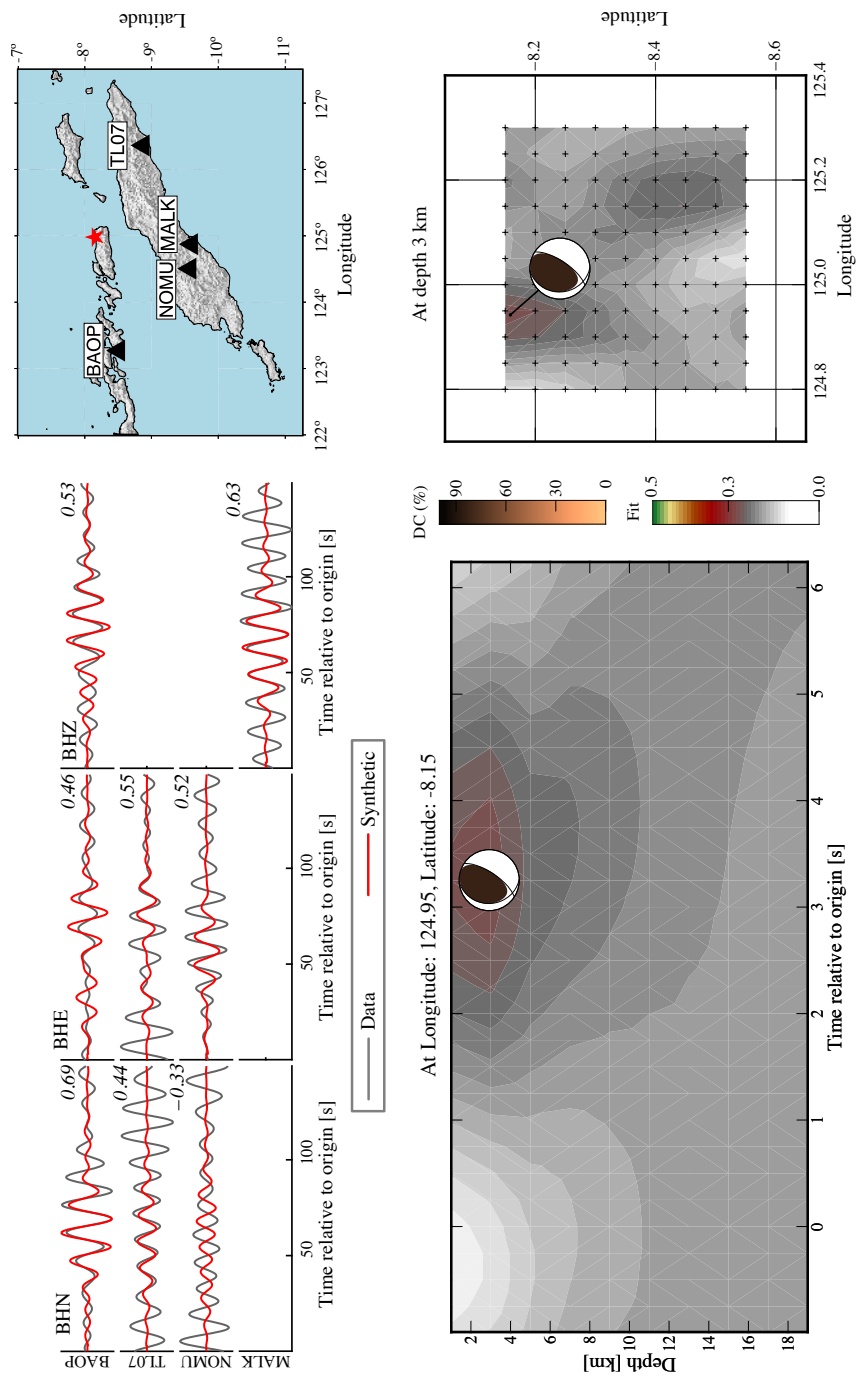


Figure A.6: Same as Fig. S4 but for the M_w 4.50 Aftershock (A1) event occurred on 2015-11-04.

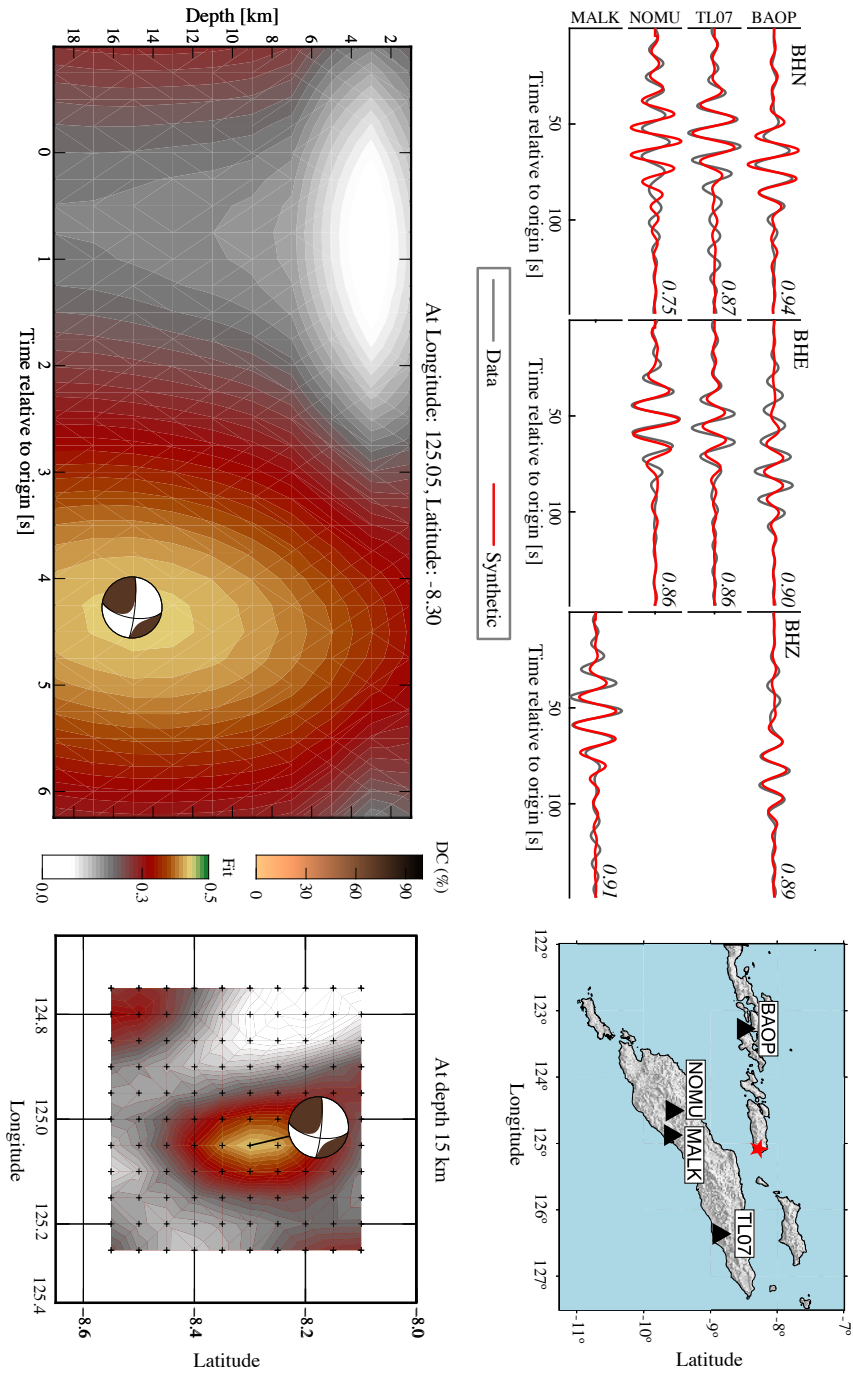


Figure A.7: Same as Fig. S4 but for the M_w 4.40 Aftershock (A2) event occurred on 2015-11-04.

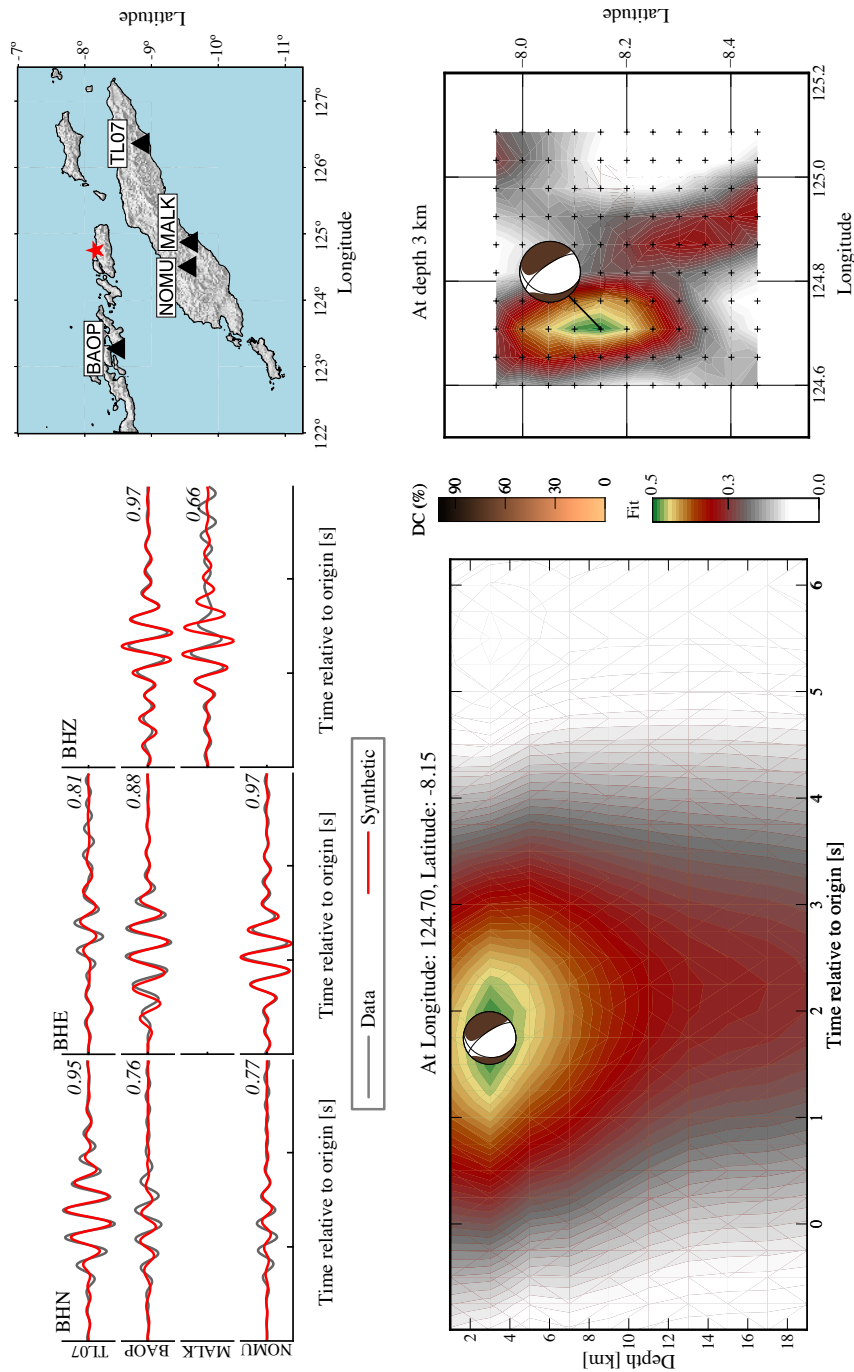


Figure A.8: Same as Fig. S4 but for the M_w 4.55 Aftershock (A3) event occurred on 2015-11-05.

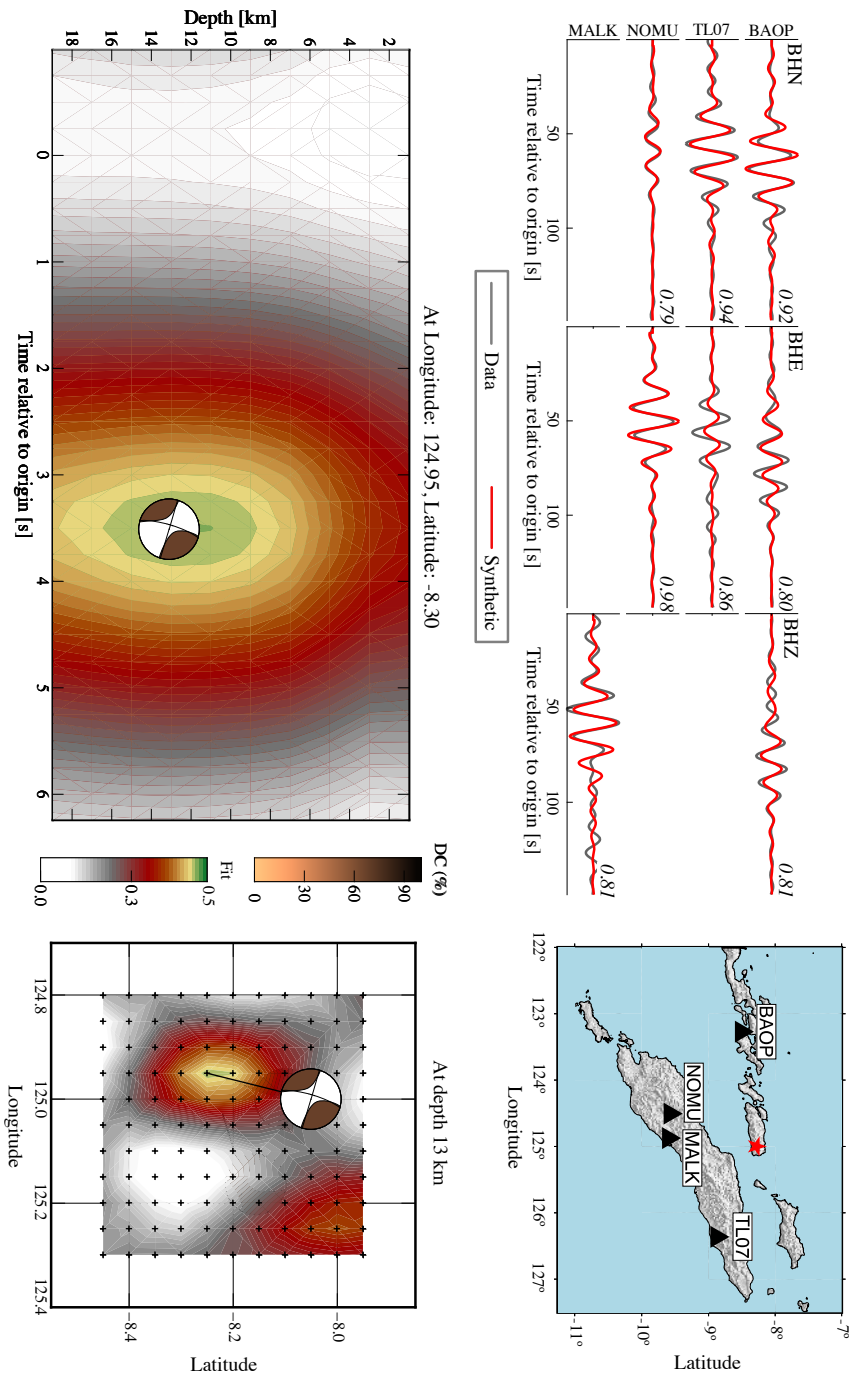


Figure A.9: Same as Fig. S4 but for the M_w 4.03 Aftershock (A4) event occurred on 2015-12-19.

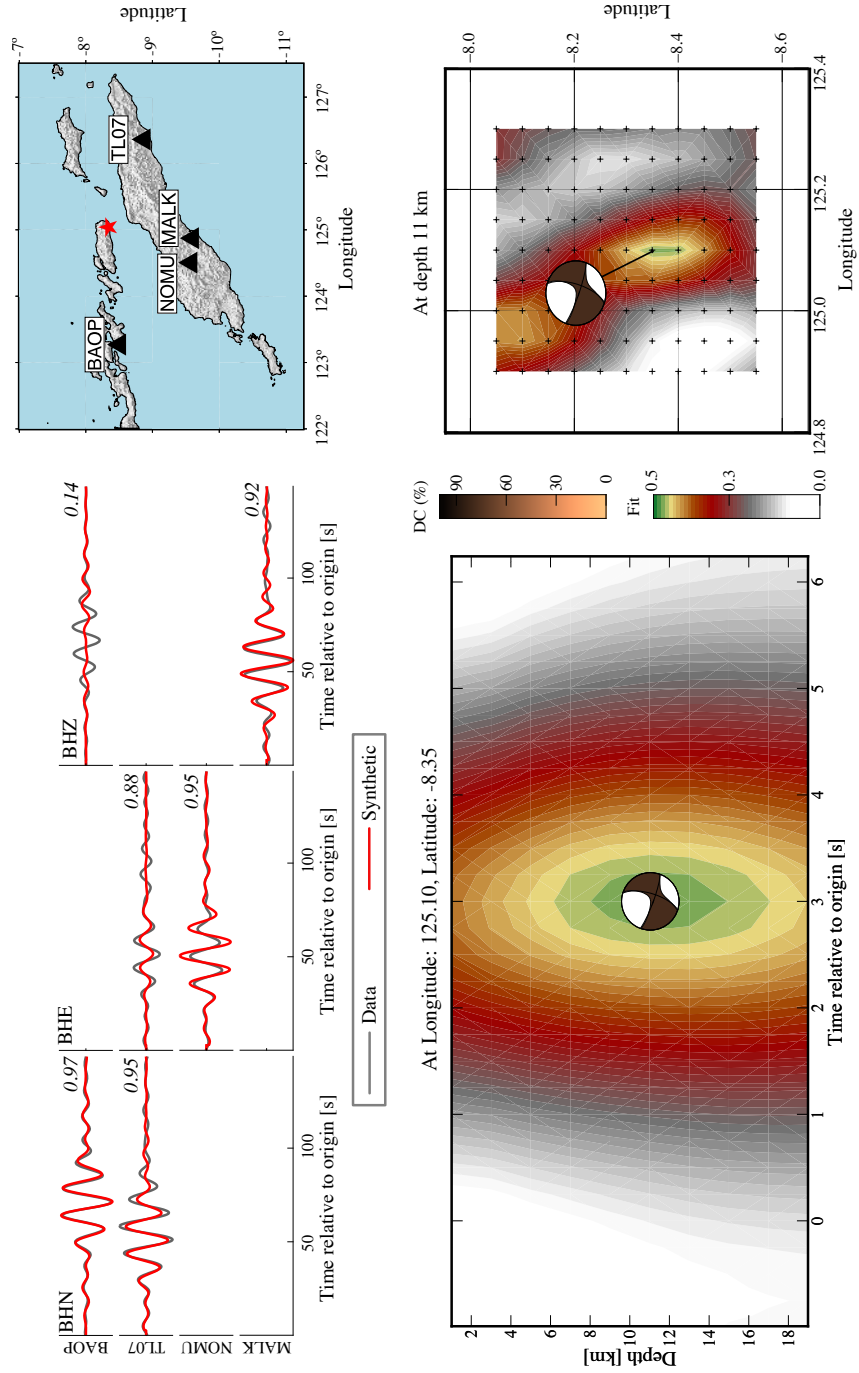


Figure A.10: Same as Fig. S4 but for the M_w 3.94 Aftershock (A5) event occurred on 2016-03-25.

Appendix B: Supplementary Materials of New Insights Into Crustal Deformation of the Indonesia–Australia–New Guinea Collision Zone From a Broad-Scale Kinematic Model

Supporting Information for
**New insights into crustal deformation of the Indonesia-Australia-New Guinea
collision zone from a broad-scale kinematic model**

Siyuan Zhao,¹ Simon McClusky¹, Phil R. Cummins¹, Meghan S. Miller¹, and
Hendro Nugroho¹

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¹Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

Additional Supporting Information <(Files uploaded separately)>

Table [B.1](#)

Datasets 1 to [B](#)

Introduction

The Supporting information contains some further details about the datasets, block models setup and the comparison of the Euler vectors derived from our best-fit model and previous studies. The [GPS](#) velocities utilized in this study are summarized in Table [B.1](#), including the location (Longitude/Latitude), velocities in the Australia-fixed reference frame, uncertainties, and the acquisition epochs. The poles of the rotation of crustal blocks with respect to the Australian Plate are illustrated in Table [B.2](#). The original reprocessed [UNAVCO GPS](#) velocities and the earthquakes that occurred during the acquisition period are illustrated in Figure [B.1](#). The reference and location of each [GPS](#) velocity used in this study are shown in Figure [B.2a-f](#). The earthquake slip vectors we calculated for constraining the inversion, the earthquake focal mechanisms used for calculating the slip vectors and the comparison between the observed and modelled earthquake slip vectors are shown in Figure [B.3a-c](#). Figure [B.4a-b](#) shows the zoomed-in view of the modelled [GPS](#) velocities in the Ramu-Markham fault zone and the Woodlark block, which corresponds to the two black rectangle areas in Figure [B.3](#). We compared the seven different block model setups with different boundary geometries, showing the residual velocities and statistic measurements in Figure [B.5](#) and summarizing the F-test statistics for the best-fit and alternative models in Table [B.3](#). Datasets 1 and [B.5](#) are the ASCII text file of the [GPS](#) velocities and earthquake slip vectors used in this study, respectively. Dataset [B](#) includes the control and input files for the modelling we performed in this study.

Lon	Lat	V _e (mm/yr)	V _n (mm/yr)	σ_e (mm/yr)	σ_n (mm/yr)	ρ (mm/yr)	Site	First Epoch	Last Epoch
<i>Tregoning et al., 1998a</i>									
155.463	-4.783	-97.731	-33.289	4.6	2.4	0	CART	1992.342	1996.675
155.833	-10.688	-5.134	3.903	2.7	1.5	0	MISI	1990.686	1996.664
154.675	-3.335	-102.337	-33.563	4.6	2.4	0	NUGU	1992.342	1996.675
152.162	-4.192	-15.07	-152.3	4.6	2.4	0	RABL	1992.324	1996.678
<i>Tregoning et al., 1998b</i>									
152.800	-11.303	-2.449	-3.658	4.2	1.8	0	BELL	...	...
160.053	-9.428	-71.454	-15.519	2.7	2.5	0	HONI	...	...
161.903	-10.452	-77.486	-20.472	5	3.9	0	KIRA	...	...
<i>Tregoning et al., 1999</i>									
149.435	-4.688	-4.51	-79.23	2	0.8	0	WITU	1990	1998
151.505	-5.645	-14.83	-107.27	3	1.2	0	JACQ	1990	1996
<i>Stevens et al., 2002</i>									
134.312	-5.987	4.73	3.1	2.5	0.6	0.096	ARUX	1992.9	1997.9
140.414	-8.467	2.65	-1.63	1.5	0.4	-0.001	AUKE	1991.5	1997.9
136.09	-1.16	-88.23	-26.92	2.2	0.7	0	BIAK	1991.4	1997.9
132.265	-2.9	-58.57	-26.75	2.9	0.9	0.034	FAKF	1992.9	1994.8
133.694	-3.62	-57.88	-8.58	2.1	0.7	0.017	KAIM	1992.9	1996
134.05	-0.886	-84.11	-29.13	2.8	0.7	0.03	MANO	1993.9	1997.9
127.644	-1.341	-87.68	-46.76	2.6	0.7	0.011	OBIX	1992.8	1994.8
140.516	-2.556	-17.18	-15.01	1.6	0.6	0.019	SENT	1991.5	1997.9
131.254	-0.869	-85.25	-34.65	2.5	0.7	0.012	SORO	1991.5	1997.9
138.95	-4.096	-8.44	-3.46	1.6	0.4	-0.011	WAMB	1991.4	1994.7
136.24	-1.862	-33.69	-35.69	2.8	0.9	0.038	YAPE	1993.8	1997.9
<i>Bock et al., 2003</i>									
132.265	-2.9	-61.18	-18.26	2.5	1.7	0	FAKF	1992	1996
133.694	-3.62	-53.92	-3.25	2	1.4	0	KAIM	1992	1996
134.05	-0.886	-76.72	-21.12	1.7	1.2	0	MANO	1992	1994
127.644	-1.341	-69.62	-54.27	3.2	2.5	0	OBIX	1992	1994
140.516	-2.556	-25.95	-19.13	1.5	0.6	0	SENT	1991	1997
131.254	-0.869	-74.77	-29.92	2.7	1	0	SORO	1991	1996
136.24	-1.862	-39.65	-16.76	5.9	5.4	0	YAPE	1992	1994
<i>Wallace et al., 2004</i>									
145.905	-6.34	-8.41	-6.56	2.9	1.9	0.052	AIYU	1993.214	2000.177
144.968	-4.295	-8.89	-13.42	1.9	1.6	-0.005	BOGI	1998.182	2001.2
146.913	-6.668	-8.88	-1.76	1.2	1	0.013	BUBI	1993.214	2000.202
147.356	-6.729	-10.21	-24.02	1.5	1.3	0.011	BUKA	1998.174	2001.206
146.6256	-7.2069	-7.93	-1.87	0.4	0.37	0.009	BULO	1998.182	2001.161
147.8549	-6.6153	-36.48	-48.76	1.98	1.76	-0.015	FINS	1997.99	2000.188
146.747	-6.443	-25.78	-25.21	1.6	1.4	-0.005	GAIX	1998.19	2000.202
145.3918	-6.0814	-9.18	-10.18	0.43	0.42	0.003	GOKA	1994.1	2000.196

Table B.1: The GPS data analyzed in the study, including the coordinates, velocity, uncertainty, and observation year for each GPS site. Lon-Longitude; Lat-Latitude; Ve-Velocity in east direction; Vn-Velocity in north direction; σ_e -Uncertainty in east direction; σ_n -Uncertainty in north direction; ρ -velocity NE correlation coefficient. The data derived from the UNAVCO are the raw GPS data processed in our study. <The Table is uploaded separately due to its large size.>

147.032	-6.568	-26.01	-22.32	1.3	1.1	-0.003	HOB	1993.218	2001.237
147.246	-6.226	-20.01	-31.15	1.7	1.4	-0.008	INDA	1998.174	2001.198
146.718	-6.461	-18.58	-19.82	1.9	1.3	-0.034	KASU	1997.98	2001.199
146.999	-6.733	-5.25	-2.63	2.2	1.4	-0.045	LAE0	1993.217	2001.208
146.9932	-6.6737	-8.32	-3.75	0.2	0.23	0.018	LAE1	1997.98	2002.96
147.579	-7.771	-5.57	2.95	2.7	1.7	0.028	MORX	1998.174	2000.189
146.715	-6.488	-19.47	-18.82	1.4	1.2	0.004	MUNG	1997.98	2001.2
146.7276	-6.5633	-7.27	-2.16	0.34	0.32	0.009	NADZ	1993.215	2001.161
146.453	-6.347	-21.55	-15.7	5.1	2.8	0.051	NARI	2000.199	2002.106
146.227	-6.179	-18.64	-17.36	2.3	1.4	0.04	NM31	1993.219	2000.199
146.169	-6.212	-7.53	-7.78	2.2	1.5	0.033	NM32	1993.219	2000.199
146.097	-6.164	-8.66	-10	1.9	1.4	0.047	NM33	1993.219	2000.199
146.081	-6.148	-8.86	-8.91	1.7	1.3	0.012	NM34	1993.219	2000.199
146.091	-6.125	-9.97	-11	2.2	1.4	0.036	NM35	1993.219	2000.199
146.101	-6.126	-10.67	-11.2	2.1	1.4	0.021	NM36	1993.219	2000.199
146.83	-6.673	-4.79	-2.28	3.1	1.6	0.022	OMSI	1993.216	2001.207
147.513	-6.445	-23.9	-35.37	1.6	1.2	0.01	PIND	1998.174	2002.098
146.459	-5.625	-15.71	-23.4	2.3	1.7	0.026	SAID	1998.183	2000.196
147.052	-7.052	-11.72	4.48	3.6	2	-0.024	SALA	2000.201	2002.132
146.321	-6.395	-8.55	-7.74	1.7	1.4	0.019	SANG	1998.188	2001.205
146.4254	-6.4192	-10.16	-12.67	2.65	2.36	0.005	SASI	2000.199	2002.106
147.056	-6.644	-7.87	-6.51	1.4	1.1	-0.003	SITU	1993.218	2001.237
146.56	-5.954	-21.88	-23.47	3.5	2.6	0.018	TEPT	1998.19	1999.149
146.552	-6.539	-9.77	-2.97	1.7	1.4	-0.016	TERE	1993.216	1998.19
145.459	-5.597	-12.22	-11.59	2.2	1.7	0.018	WALI	1998.183	2000.196
146.469	-6.135	-23.43	-22.79	1.6	1.3	0.002	WANT	1998.182	2001.2
147.195	-5.962	-19.82	-37.37	1.8	1.3	0.003	WASU	1998.174	2001.2
146.867	-6.602	-9.21	-1.37	1.2	1	-0.005	YALU	1993.217	2000.202

Wallace et al, 2014

150.337	-10.31	0.82	1.08	0.52	0.99	0	ALT2	2002	2012
150.832	-9.465	1.77	13.91	1.11	1.38	0	BASM	2009	2012
149.473	-9.608	1.35	5.55	0.83	0.58	0	BAYA	2009	2012
151.185	-9.94	2.89	3.37	1.27	1.09	0	BWAR	2009	2012
150.426	-10.407	1.55	2.04	0.93	0.83	0	DAIO	2009	2012
151.015	-9.927	0.58	3.18	0.99	1.19	0	DARB	2009	2012
151.204	-10.1	1.98	3.71	0.96	1.14	0	DIGA	2009	2012
150.812	-9.73901	3.33	5.65	0.84	0.8	0	ESAA	1996	2010
149.794	-9.77	3.51	7.07	0.55	1.06	0	GIWA	2009	2012
152.944	-9.225	-9.4	24.21	1.09	0.46	0	GUA1	2009	2012
150.865	-9.21	-1.04	16.25	1.81	1.81	0	GUMA	2009	2012
150.873	-10.226	1.6	3.34	1.29	0.95	0	HEHE	2009	2012
150.102	-10.095	1.95	3.4	0.7	0.92	0	JONE	2009	2012
150.299	-8.522	-7.51	15.14	1.48	1.24	0	KAWA	2009	2012
150.554	-10.212	1.94	2.62	1.52	1.03	0	KEIA	2009	2012

Table B.1: Part 2

151.036	-10.1	1.74	1.98	1.8	0.69	0	KURA	2009	2012
151.274	-9.923	0.73	4.11	1.16	0.68	0	KWAN	2009	2012
150.712	-9.311	-1.04	15.72	0.85	0.85	0	KWAT	2009	2012
150.728	-10.302	1.16	0.36	0.8	1.47	0	LELE	2009	2012
151.125	-8.535	-8.59	15.6	0.89	0.29	0	LOS2	1997	2012
150.437	-9.6	1.92	7.98	1.72	1.16	0	MAPA	2009	2012
149.936	-9.757	2.44	6.93	0.27	1.58	0	MENA	2009	2012
149.866	-10.398	1.22	0.68	0.49	0.57	0	NUBE	2009	2012
149.795	-9.621	3.44	6.91	0.54	0.68	0	PEMM	2009	2012
150.795	-9.663	2.63	9.86	1.56	0.9	0	SALM	2004	2012
150.268	-10.683	0.71	1.65	0.95	0.65	0	SIBA	2009	2012
149.707	-9.84	3.99	2.39	0.83	2.28	0	SIRI	2009	2012
150.662	-10.613	0.48	1.62	0.45	0.69	0	SMRI	2009	2012
151.867	-10.225	2.59	4.2	0.85	0.48	0	STRA	2009	2012
149.323	-9.08	-2.87	7.69	1.64	1.13	0	TUFI	2004	2006
150.953	-9.452	0.66	16.21	1.72	1.64	0	UAMA	2009	2012
151.183	-8.853	-3.74	18.8	0.68	0.61	0	VAKU	2009	2012
150.324	-9.31	1.01	10.36	0.58	0.48	0	VIVI	2004	2008
150.532	-9.355	0.36	13.77	1.72	2.1	0	WAPO	2009	2012
150.242	-9.211	0.11	11.07	0.83	0.46	0	WATL	2004	2012
151.896	-9.271	0.39	20.48	1.16	1.08	0	YANA	2009	2012
<i>Kreemer et al., 2014</i>									
135.712	-3.541	-16.84	-15.59	0.56	0.52	0.053	64KM	...	...
136.101	-1.175	-81.29	-20.57	0.15	0.11	0.02	BIAK	...	...
140.414	-8.467	-0.59	0.29	0.15	0.12	0.001	AUKE	...	...
134.072	-0.859	-79.14	-35.61	0.83	0.68	-0.011	CMAN	...	...
135.505	-3.367	-26.79	-27.69	0.43	0.35	0.054	CNAB	...	...
115.471	-8.543	-12.45	-63.47	0.52	0.42	0.024	CPBI	...	...
135.73	-3.176	-25.55	-15.93	0.34	0.28	0.014	LEGA	...	...
127.099	-3.271	-21.19	-24.28	3.36	2.79	-0.068	NAML	...	...
134.169	-1.506	-80.17	-23.44	0.54	0.5	-0.036	RANS	...	...
140.516	-2.556	-25.13	-17.34	0.52	0.32	0.005	SENT	...	...
131.254	-0.875	-97.26	-25.27	1.96	1.66	-0.115	SORO	...	...
138.752	-1.872	-82.58	-8.15	0.28	0.23	-0.012	SRMI	...	...
135.588	-3.487	-24.95	-20.2	0.5	0.44	0.016	TOPO	...	...
137.092	-4.145	2.64	-4.29	2.6	2.29	0.062	TPRA	...	...
138.95	-4.096	-5.44	-2.52	0.48	0.35	0.062	WAMB	...	...
134.508	-2.728	-47.72	1.04	0.98	0.79	-0.009	WASI	...	...
136.38	-2.241	-5.67	-38.78	3.15	2.53	0.005	WREN	...	...
136.24	-1.862	-33.48	-11.46	0.1	0.17	0	YAPE	...	...
134.945	-3.248	-32.74	-29.98	0.74	0.6	0.022	YEUR	...	...
<i>Koulali et al., 2015</i>									
142.825	-4.2188	-5.81	-2.95	0.88	0.83	0.004	ABTI	2003.903	2007.903
141.267	-7.3477	0.02	-0.29	0.33	0.29	0.011	AIAM	1993.708	2013.108

Table B.1: Part 3

143.499	-4.6062	-9.56	-4.99	0.84	0.78	0.011	AMBN	2004.408	2008.49
144.073	-4.0576	-11.23	-7.63	1.88	1.7	0.002	ANGR	2000.572	2007.903
140.704	-2.5146	-22.19	-10.58	0.55	0.54	0.001	ANGS	1997.245	2001.689
144.819	-3.5975	-10.38	-19.5	0.89	0.85	0.002	BAMI	2000.736	2008.49
141.167	-3.0231	-22.64	-11.5	1.36	1.31	0.007	BEWA	2003.985	2007.985
146.625	-7.2069	-7.93	-1.87	0.4	0.37	0.009	BULO	1998.508	2014.073
147.854	-6.6153	-36.48	-48.76	1.98	1.76	0.015	FINS	1997.327	2000.514
143.722	-6.8793	-1.11	-0.64	1.18	1.06	0.124	GOB1	2007.947	2013.842
145.391	-6.0814	-9.18	-10.18	0.43	0.42	0.003	GOKA	1993.708	2006.656
144.306	-5.8322	-8.15	-7.36	0.4	0.38	0.002	HGEN	1997.41	2008.408
146.034	-7.5011	-6.45	-6.77	0.96	0.91	0.002	KAIN	2003.738	2007.985
150.806	-2.5814	-94.16	-26.74	1.45	1.28	0.036	KAVI	1993.432	2002.985
145.771	-7.9577	-3.61	-5.92	0.85	0.8	0.021	KERE	2003.738	2011.029
144.248	-7.4235	-0.32	-1.55	0.56	0.45	0.044	KIKO	1993.708	2009.755
141.278	-6.1272	1.21	0.24	0.66	0.58	-0.021	KIUN	1997.327	2005.574
144.185	-7.3221	0.12	-0.98	1.13	0.95	0.002	KOPB	2005.541	2013.593
145.955	-7.1969	-7.01	-6.52	0.83	0.79	0.002	KWAP	2003.738	2007.985
146.993	-6.6737	-8.32	-3.75	0.2	0.23	0.018	LAE1	1996.676	2006.574
145.782	-5.2115	-11.4	-16.73	0.85	0.81	0.002	MAD1	1993.708	2000.572
146.02	-7.2167	-7.7	-6.67	0.8	0.78	0.001	MENY	2003.738	2007.985
147.186	-9.4341	-2.79	-3.29	0.36	0.35	0.008	MORE	1993.432	2005.574
146.727	-6.5633	-7.27	-2.16	0.34	0.32	0.009	NADZ	1997.327	2014.095
141.141	-5.6673	0.26	-0.84	1.01	0.55	0.013	NING	1993.708	2006.656
147.366	-2.0432	-98.52	-31.43	0.34	0.43	0.006	PNGM	2002.41	2014.095
141.22	-5.2576	0.21	0.45	0.67	0.58	-0.008	TABU	1997.327	2006.656
144.076	-3.2385	-94.69	-30.31	0.91	0.86	-0.004	TARO	2000.736	2008.49
141.643	-5.1257	-1.88	-0.7	1.12	1.07	-0.001	TELE	2003.821	2006.656
143.836	-3.7923	-9.64	-6.77	1.84	1.68	0.004	TRNG	2000.572	2007.903
141.304	-2.6848	-19.89	-8.23	0.47	0.46	-0.001	VANI	1993.627	2007.985
143.666	-3.584	-14.42	-6.5	0.56	0.51	0.001	WEWK	1993.708	2012.523
144.293	-6.6587	-3.92	-3.81	1.88	1.84	0.026	WOPA	2006.656	2008.49
142.836	-1.7354	-100.3	-37.03	0.73	0.66	0.004	WUVU	1993.708	1999.985
141.095	-4.6293	-5.22	-0.63	0.5	0.46	-0.001	YAPS	1997.656	2006.738

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121.019	-8.821	-10.11	-41.49	0.51	0.48	-0.011	3042	1993.825	2013.805
121.988	-10.466	-4.86	-33.77	0.5	0.48	-0.002	3049	1993.912	2013.808
121.783	-10.522	-4.9	-33.16	0.5	0.48	-0.001	3050	1993.912	2013.816
117.415	-8.489	-10.76	-57.44	0.52	0.49	0.001	3066	1993.745	2013.805
116.36	-8.635	-9.37	-59.1	5.85	5.14	-0.004	3074	1994.071	2013.805
122.829	-10.807	-5.26	-27.05	0.6	0.55	-0.017	3022	1993.912	2013.797
123.473	-8.33	-8.98	-34.39	0.53	0.49	0.005	3032	1994.036	2013.825
123.001	-8.275	-6.2	-38.92	2.48	2.32	0.011	3034	1993.855	2003.77
124.035	-5.905	-11.42	-41.46	1	0.92	-0.028	491A	2006.712	2014.258
133.886	-23.67	0.173	0.199	0.253	0.246	-0.003	ALIC	1997.027	2014.282

Table B.1: Part 4

116.101	-8.561	-11.8	-60.48	0.68	0.46	-0.007	ANAN	1993.721	2013.811
120.482	-6.492	-10.41	-62.11	0.89	0.79	-0.022	APTC	2006.704	2014.241
114.68	-8.147	-10.6	-64.6	1.08	0.96	0.021	BALI	1996.295	2007.416
122.599	-5.609	-13.57	-55.06	0.76	0.71	0.034	BBAU	2006.726	2014.274
118.693	-8.543	-13.65	-54.54	0.94	0.88	-0.001	BIMA	1993.778	2013.795
113.094	3.24	-11.35	-67.1	0.75	0.3	0	BIN1	2007.715	2014.263
113.067	3.262	-8.64	-67.76	0.39	0.43	-0.008	BINT	1999.085	2002.775
116.815	-1.272	-15.95	-67.41	1.24	0.85	0.037	BLKP	1998.734	2006.825
128.1849	-3.6956	-28.26	-33.6	0.3	0.3	0	CAMB	2010.797	2013.997
116.84	-1.256	-14.29	-66.88	1.68	1.71	-0.002	CBAL	2010.027	2012.309
121.078	-7.382	-9.43	-57.4	0.76	0.66	-0.008	CBON	2009.885	2013.91
114.44	-7.838	-11	-65.94	1.65	1.58	-0.004	CBRN	2008.495	2011.236
110.335	-7.893	-14.08	-63.71	6.31	6.25	-0.002	CBTL	2011	2013.997
114.628	-8.393	-11.87	-63.06	0.4	0.35	0	CCAK	2008.369	2012.413
122.868	-8.069	-6.51	-38.18	1	0.95	-0.001	CDAI	2009.858	2013.896
115.146	-8.818	-11.2	-61.6	0.31	0.3	-0.004	CDNP	2008.369	2013.74
113.693	-8.175	-13.57	-62.7	1.15	1.14	-0.001	CJEM	2011	2013.849
110.667	-6.596	-17.65	-65.43	1.38	1.32	-0.002	CJPR	2011	2013.786
124.517	-8.213	-8.54	-28.19	0.62	0.64	-0.002	CKAL	2009.888	2013.997
122.545	-3.963	-13.19	-50.91	1.16	1.15	-0.001	CKEN	2010.723	2013.992
123.597	-10.169	-1.28	-23.65	0.5	0.41	-0.002	CKUP	2009.868	2013.981
122.11	-8.121	-3.67	-51.86	1.14	1.13	0	CKUR	2009.871	2013.899
116.076	-8.728	-9.16	-59.43	1.09	1.11	-0.001	CLBR	2008.557	2011.997
112.327	-7.093	-13.25	-65.55	0.57	0.56	-0.001	CLMG	2011	2013.997
113.115	-8.214	-12.08	-65.6	1.19	1.44	-0.002	CLUM	2011	2012.287
123.422	-8.371	-9.02	-35.78	0.62	0.57	-0.011	CLWB	2009.868	2013.948
111.451	-7.606	-11.8	-62.66	0.57	0.52	0	CMAG	2011	2013.997
119.408	-5.135	-11.61	-64.69	0.64	0.37	-0.003	CMAK	2009.997	2013.997
110.217	-7.476	-14.75	-64.64	4.54	4.48	-0.001	CMGL	2011	2013.997
112.442	-7.466	-10.47	-64.88	0.84	0.76	-0.004	CMJT	2011	2012.964
112.663	-7.98	-12.87	-63.58	0.68	0.57	-0.004	CMLG	2011	2013.997
122.22	-8.627	-9.16	-32.69	0.39	0.42	-0.01	CMRE	2009.841	2013.997
114.375	-8.212	-12.15	-63.52	2.29	2.26	0	CNYU	2011	2013.115
96.834	-12.188	0.15	-0.65	0.42	0.43	-0.005	COCO	1997.016	2014.282
111.098	-8.196	-12.93	-63.01	0.64	0.58	-0.001	CPAC	2011	2013.997
113.53	-7.719	-11.79	-59.76	1.25	1.26	-0.012	CPAI	2011	2013.814
112.901	-7.651	-12.62	-61.97	0.55	0.64	-0.001	CPAS	2011	2013.997
115.471	-8.543	-12.212	-62.309	0.63	0.56	0.016	CPBI	2008.407	2011.074
122.319	-8.348	-10.06	-37.48	0.35	0.35	-0.002	CPBR	2009.852	2013.997
114.11	-8.534	-12.42	-62.5	1.86	1.84	0	CPES	2011	2013.477
109.329	-0.004	-12.43	-65.77	1.3	1.11	-0.058	CPON	2010.781	2012.309
110.914	-7.096	-15.99	-65.75	0.74	0.67	-0.004	CPWD	2011	2013.512
120.49	-8.311	-10.67	-45.49	0.53	0.51	-0.004	CREO	2009.888	2013.951
110.377	-6.987	-16.89	-65.91	0.55	0.55	0.001	CSEM	2011	2013.997

Table B.1: Part 5

114.013	-7.703	-12.43	-62.93	0.59	0.58	-0.005	CSIT	2011	2013.997
113.875	-7.018	-13.27	-66.19	0.56	0.54	0	CSMN	2011	2013.997
113.252	-7.195	-13.65	-66.15	0.56	0.56	-0.001	CSMP	2011	2013.997
111.986	-6.872	-15.87	-65.59	0.7	0.57	-0.002	CTBN	2011	2013.997
121.768	-7.406	-7.2	-55.75	1.02	1	-0.001	CTOA	2009.877	2013.904
111.906	-8.066	-12.55	-63.61	0.6	0.55	0	CTUL	2011	2013.997
123.753	-5.503	-14.18	-44.17	1.03	0.92	-0.044	D490	2006.707	2014.252
131.133	-12.844	-0.169	0.146	0.305	0.317	0	DARW	1994.641	2014.282
72.37	-7.27	3.17	-0.48	0.53	0.3	-0.001	DGAR	1997	2014.282
121.766	-8.707	-7.14	-36.34	0.57	0.55	-0.021	ENDE	1996.295	2013.836
102.105	6.226	-2.28	-57.22	0.98	0.96	-0.005	GETI	1999.83	2002.745
133.694	-3.645	-55.806	-3.9133	1.39	0.865	0.01	KAIM	1994.595	2011.877
124.28	-9.776	3.24	-18.15	0.51	0.48	-0.005	KAPA	1996.295	2013.822
117.097	-20.981	-0.64	0.19	0.3	0.3	0.005	KARR	1997.027	2014.282
119.492	-8.589	-12.19	-48.08	3.72	1.34	0.012	KOMO	...	...
119.88	-8.489	-11.12	-40.26	4.87	1.74	0.054	LABU	...	...
125.739	-8.059	0.89	-12.76	0.5	0.49	-0.003	LIRA	1996.295	2013.808
120.905	-2.595	-17.86	-58.65	2.04	1.34	0.022	MLLX	1996.295	1999.715
103.68	1.346	-5.97	-56.77	1.73	0.94	-0.002	NTUS	1997.66	2014.282
119.65	-3.978	-14.24	-65.28	0.56	0.52	-0.01	PARN	2006.792	2010.866
127.369	-7.59	-0.45	-10.04	0.56	0.53	0.021	ROMA	2002.386	2013.827
120.478	-8.597	-10.76	-41.35	0.57	0.52	-0.011	RUTE	1993.644	2013.797
110.799	-8.191	-15.01	-62.48	4.95	4.88	-0.003	SADE	2011.003	2012.997
98.715	3.622	-5.02	-50.31	0.66	1.07	0	SAMP	1998.663	2010.633
148.98	-35.399	4.88	-3.57	3.62	2.94	-0.01	TIDB	1993.633	2014.282
122.075	-5.474	-10.3	-57.82	0.92	0.87	0.026	TLGA	2006.723	2014.282
117.641	0.558	-17.65	-68.01	1.05	0.99	-0.005	TNJB	2002.784	2006.803
121.489	-4.582	-13.89	-59.98	0.83	0.7	0.008	TOAR	1996.295	2008.951
147.056	-19.269	0.11	-0.27	0.3	0.3	0	TOW2	1997	2014.282
119.549	-5.06	-11.39	-65.29	0.47	0.45	0.004	UJPD	1994.638	2008.921
110.425	1.468	-12.84	-65.65	0.5	0.39	-0.002	UMAS	2007	2014.263
116.112	6.039	-8.66	-68.16	0.35	0.73	0	UMSS	2007	2014.263
119.219	-9.39	-9.43	-43.57	0.3	0.3	0	WAIK	2008.199	2013.83
120.301	-9.669	-7.64	-39.93	0.48	0.47	-0.002	WAIN	1993.896	2013.833
126.429	-7.935	0.93	-10.99	0.58	0.52	-0.024	WETA	1993.992	2013.819
123.539	-5.328	-16.9	-44.33	3.63	3.16	0.014	WNG1	2008.926	2014.263
115.347	-29.047	-0.58	0.22	0.3	0.3	-0.012	YAR2	1998	2014.282
<i>Koulali et al., 2017</i>									
109.653	-7.67	-15.27	-64.02	0.74	0.67	-0.001	CKBM	2011.001	2013.999
110.208	-7.635	-11.63	-64.16	0.94	0.72	0.012	BUTU	1996.296	2008.488
110.295	-7.817	-13.42	-66.67	1.35	1.32	0.002	JOGS	2008.46	2013.999
110.926	-7.814	-9.35	-64.69	1.55	1.23	-0.085	WGIR	2004.766	2010.448
111.475	-7.847	-10.69	-62.32	1.26	1.07	-0.032	PONO	2004.789	2013.999
112.714	-7.71	-11.53	-62.58	1.62	1.22	-0.058	SKOR	2004.783	2010.379

Table B.1: Part 6

115.058	-8.15	-10.22	-66.53	0.42	0.41	-0.006	CSRJ	2008.553	2013.741
114.389	-8.451	-7.2	-62.77	1.83	2.02	0.003	CMCR	2008.37	2011.237
<i>Biemiller et al., 2020</i>									
149.308	-9.648	2.84	6.04	0.73	0.61	0	BINI	2015	2018
149.459	-9.684	2.27	5.5	0.78	0.64	0	BORO	2015	2018
149.289	-9.835	2.65	-1	1.88	1.6	0	DD01	2015	2016
149.434	-9.661	3.41	5.87	0.68	0.56	0	GONO	2015	2018
149.362	-9.597	2.33	7.54	0.61	0.51	0	GOUR	2015	2018
149.33	-9.624	0.89	4.86	2.64	2.05	0	KABU	2015	2016
150.43	-9.414	1.26	8.84	0.24	0.22	0	KALO	2009	2018
149.381	-9.577	1.53	8.03	0.68	0.57	0	KIBU	2015	2018
150.292	-9.496	1.65	8.79	0.26	0.23	0	KILI	2009	2018
150.187	-9.432	0.2	8.95	0.24	0.22	0	MORA	2009	2018
149.422	-9.61	3.21	8.16	0.79	0.63	0	MORB	2015	2018
149.834	-9.972	2.34	3.46	0.12	0.1	0	RABA	2010	2018
149.393	-9.557	2.05	8.36	0.75	0.61	0	RAKO	2009	2018
149.318	-9.079	-1.52	7.65	0.25	0.23	0	TUF2	2009	2018
150.139	-9.245	0.32	11.4	0.26	0.24	0	WAIB	2009	2018
149.157	-9.338	-0.18	6.93	0.42	0.35	0	WANI	2009	2018
149.279	-9.7	-1.41	1.69	2.5	2.18	0	YAMS	2015	2016
<i>Cummins et al., 2020</i>									
130.488	-3.104	-44.82	-16.12	1	1	0	CBLA	...	...
131.298	-7.9842	-2.33	-1.84	0.3	0.4	0	CSAU	...	...
132.745	-5.632	-17.96	1.95	0.2	0.2	0	CUAL	...	...
<i>Meilano et al., 2021</i>									
128.08	-3.71	-29.33	-42.59	0.3	0.26	0	AMB1	...	...
128.19	-3.06	-42.87	-44.79	0.49	0.36	0	PIRU	...	...
128.96	-3.3	-31.73	-46.33	0.29	0.22	0	MSHI	...	...
<i>This Study (Reprocessed UNAVCO raw data)</i>									
140.301	-6.099	5.21	1	1.48	1.14	-0.013	TNMH	2002.126	2004.333
138.95	-4.096	-1.77	-5.77	1.11	0.86	0.052	WAMB	2002.178	2004.325
137.118	-4.044	12.39	-12.38	1.82	1.68	0.057	NORA	2002.142	2004.322
137.114	-4.068	9.96	-8.84	2.03	1.59	0.017	KIMG	2002.148	2004.319
137.092	-4.144	6.99	-3.75	2.85	2.51	0.067	TPRA	2002.14	2004.32
137.009	-4.285	13.45	-4.66	1.75	1.42	-0.008	TP50	2002.132	2004.314
136.895	-4.534	8.82	-3.42	0.89	0.73	0.007	TIMI	2002.126	2004.309
136.841	-4.829	8.96	1.7	2.53	2.23	0.011	AMAR	2002.126	2004.311
138.752	-1.872	0.22	0.97	0.22	0.97	0	SRMI	...	2004.344
136.381	-3.927	17.3	-11.07	1.53	1.27	-0.065	TALI	2002.195	2004.331
136.24	-1.874	-25.32	-32.09	1.16	0.88	-0.01	YAPE	2002.184	2004.363
136.104	-1.19	-76.07	-22.43	1.18	0.83	0.007	BIAX	2002.126	2004.366
136.019	-2.696	-41.04	-24.03	2.73	2.29	-0.016	WAPO	2002.17	2004.35
140.516	-2.573	0.02	0.71	0.02	0.71	0	SENT	2002.158	2004.342

Table B.1: Part 7

135.692	-1.629	-38.98	-49.68	2.54	2.01	-0.107	POM2	2002.189	2004.374
134.827	-1.065	-101.06	-82.47	2.23	1.52	-0.101	NUMF	2002.175	2004.38
133.694	-3.645	-71.62	24.81	1.43	1.11	-0.013	KAIM	2002.162	2004.35
131.254	-0.875	-100.69	-24.2	1.62	1.09	-0.06	SORO	2002.142	2004.36
140.414	-8.518	1.11	1.08	1	0.77	-0.003	BUKE	2002.145	2004.322
<i>This Study (New acquisition)</i>									
125.528	-8.549	-0.6	-13.27	1.51	1.52	0.003	DILI	2018	2019
125.654	-9.002	-0.19	-10.54	3.51	2.88	-0.022	SAME	2005	2019



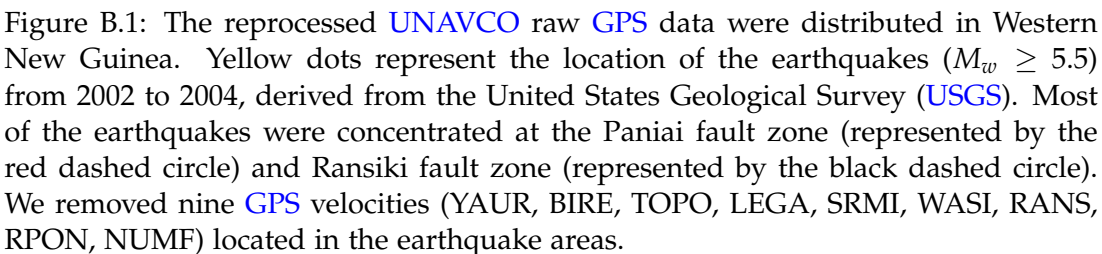
Table B.1: part 8

Plates (Block name/Ref. Block name)	References	Lon	Lat	ω , °/Myr	Sig. ω , °/Myr	E _{max} (deg)	E _{min} (deg)
BRHD/AUST	This study	135.9766	-15.3953	2.8158	0.1100	0.94	0.15
	Bock et al. (2003)	136.6	14.2	2.92	0.45	1.4	0.4
	Stevens et al. (2002)	141.3	-24.6	1.80	0.16	2.4	0.4
ADBL/AUST	This study	142.4548	-2.8523	-4.0496	0.9314	0.88	0.22
	Koulali et al. (2015)	142.9037	-2.9616	-4.8847	1.4289	0.85	0.24
FORE/AUST	This study	145.2494	-10.4312	1.2303	0.6980	6.28	0.51
	Koulali et al. (2015)	137.5844	2.7800	-1.0166	0.2664	3.35	0.33
WDBL/AUST	This study	147.8199	-9.1832	2.6104	0.0612	0.08	0.06
	Biemiller et al. (2020)	148.92	-10.97	2.81	0.4	0.77	0.19
	Koulali et al. (2015)	147.9397	-9.6108	2.7723	0.1665	0.28	0.11
	Wallace et al. (2014)	147.85	-9.54	2.69	0.13	0.26	0.15
	Wallace et al. (2004)	147.6	-11.28	2.82	0.18	0.55	0.21
	Tregoning et al. (1998)	145.2	-10.8	1.86	0.03	2.01	1.58
ENGH/AUST	This study	140.7090	-0.2736	-0.7844	0.1220	1.37	0.29
	Koulali et al. (2015)	140.9497	-1.5336	-0.9324	0.1043	0.73	0.22
	Wallace et al. (2004)	145.98	-7.56	1.63	0.20	0.36	0.18
NBBL/AUST	This study	177.2547	-60.1619	1.0706	0.0484	6.98	0.54
	Koulali et al. (2015)	168.4627	-50.8817	1.2042	0.0593	4.88	0.33
	Wallace et al. (2004)	165.31	-51.30	1.25	0.06	4.71	0.35
	Tregoning (2002)	166.7	-50.6	1.23	0.07	4.1	0.4
SBBL/AUST	This study	144.6997	-4.6306	-8.9887	0.3484	0.22	0.08
	Koulali et al. (2015)	144.4875	-4.5956	-7.8363	0.3462	0.31	0.1
	Wallace et al. (2004)	144.02	-4.18	-7.45	0.13	0.14	0.05
	Tregoning et al. (1999)	144.54	-4.36	-7.91	0.33	0.24	0.16
PPBL/AUST	This study	148.3148	-12.5216	0.5827	0.1153	1.63	0.36
	Biemiller et al. (2020)	149.23	-9.40	0.73	0.28	0.91	0.6
	Koulali et al. (2015)	148.3821	-10.6011	0.9335	0.1310	0.51	0.27
	Wallace et al. (2014)	149.29	-9.75	0.66	0.15	0.7	0.4
PAC/AUST	This study	185.8664	-55.7978	1.0240	0.0049	0.66	0.15
	Koulali et al. (2015)	183.7016	-60.2746	1.0877	0.0007	0.1	0.04
	Wallace et al. (2004)	184.48	-61.08	1.079	0.003	0.2	0.16
	Beavan et al. (2002)	184.19	-61.04	1.078	0.004	0.37	0.17
	Tregoning (2002)	184.9	-60.9	1.077	0.008	0.8	0.5
	Stevens et al. (2002)	181.7	-60.1	1.07	0.02	1.0	0.9
	Tregoning et al. (1998)	181.68	-61.4	1.01	0.02	2.38	2.28
	Larson et al. (1997)	182.9	-65.7	1.04	0.02	1.7	1.5
	Argus & Gordon (1991)	186.5	-57.2	1.13	0.04	2.6	2.4
CEND/AUST	This study	134.5145	-0.5068	-10.3731	0.6058	0.21	0.06
WNGH/AUST	This study	139.0412	-6.3263	2.9372	0.1759	0.32	0.16
BAND/AUST	This study	124.0263	-0.5169	-5.1115	0.6010	0.87	0.03
SERA/AUST	This study	132.4682	-7.6493	5.0112	0.1171	0.10	0.05
EJAV/AUST	This study	177.2012	-13.8412	0.6559	0.0372	9.52	0.25
SUMB/AUST	This study	131.9447	-11.4175	2.0616	0.0194	0.18	0.04
TIMO/AUST	This study	132.1211	-8.5504	1.0428	0.0345	0.19	0.14
WMAK/AUST	This study	179.6526	-12.7227	0.6893	0.0151	3.41	0.25
EMAK/AUST	This study	137.3037	-8.5737	1.9962	0.1885	2.17	0.20
AUST/SUND	This study	57.6670	9.0834	-0.7495	0.0115	1.67	0.19
	Koulali et al. (2016)	62.55	7.07	0.79	0.002	0.26	0.11
BAND/SUND	This study	132.0424	-1.9371	-4.8648	0.6020	0.76	0.08
	Socquet et al. (2006)	113.3	-9.7	1.80	0.21	2.55	0.63
EMAK/SUND	This study	118.2417	-4.5975	2.2364	0.1965	0.48	0.20
	Koulali et al. (2016)	115.80	-4.38	1.76	0.10	0.61	0.28
TIMO/SUND	This study	102.0113	-1.4797	1.4219	0.0358	0.96	0.19
	Koulali et al. (2016)	103.88	-1.63	1.58	0.09	1.96	0.17
SUMB/SUND	This study	114.1624	-7.0809	2.3507	0.0274	0.14	0.08
	Koulali et al. (2016)	113.53	-7.28	2.53	0.07	0.32	0.07
EJAV/SUND	This study	110.0985	-3.1586	0.7001	0.0876	0.94	0.32
	Koulali et al. (2016)	111.03	-2.45	0.66	0.29	3.22	0.74
WMAK/SUND	This study	113.7154	-2.7877	0.6883	0.0378	0.47	0.31
	Koulali et al. (2017)	113.5339	-3.5800	0.8247	0.0676	0.59	0.29
	Koulali et al. (2016)	113.58	-3.32	0.70	0.025	0.38	0.20

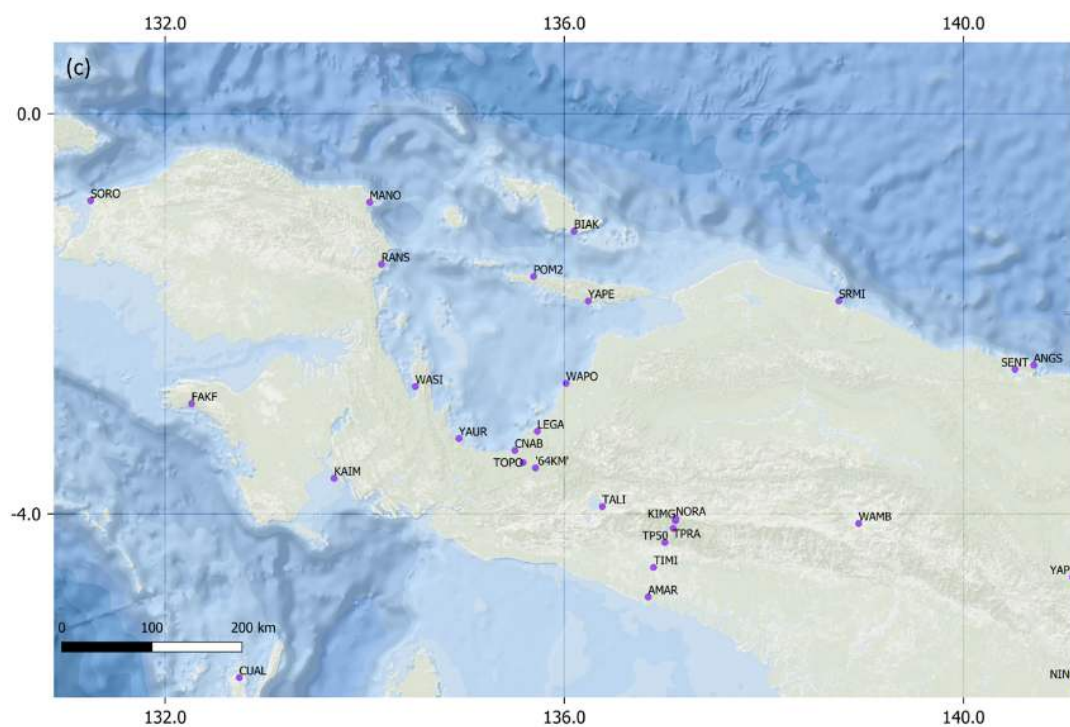
Table B.2: Summary table of the Euler vectors derived from this and previous studies. Lon and Lat represent the position of the relative Euler Pole, ω refers to the rotation rate (positive value represents anticlockwise rotation), Sig. ω refers to the standard error of our estimated rotation rate; E_{max} and E_{min} are the maximum and the minimum axis of longitude/latitude error ellipses, respectively.

Model	Nb.data	Nb.Parm	DOF	χ^2	F-prob
Model A	1026	122	904	9.4	--
Model B	1026	120	906	14.6	99%
Model C	1026	118	908	11.1	99%
Model D	1003	117	886	10.4	93%
Model E	1003	118	885	9.9	78%
Model F	1026	118	908	10.6	96%
Model G	1026	118	908	11.4	99%

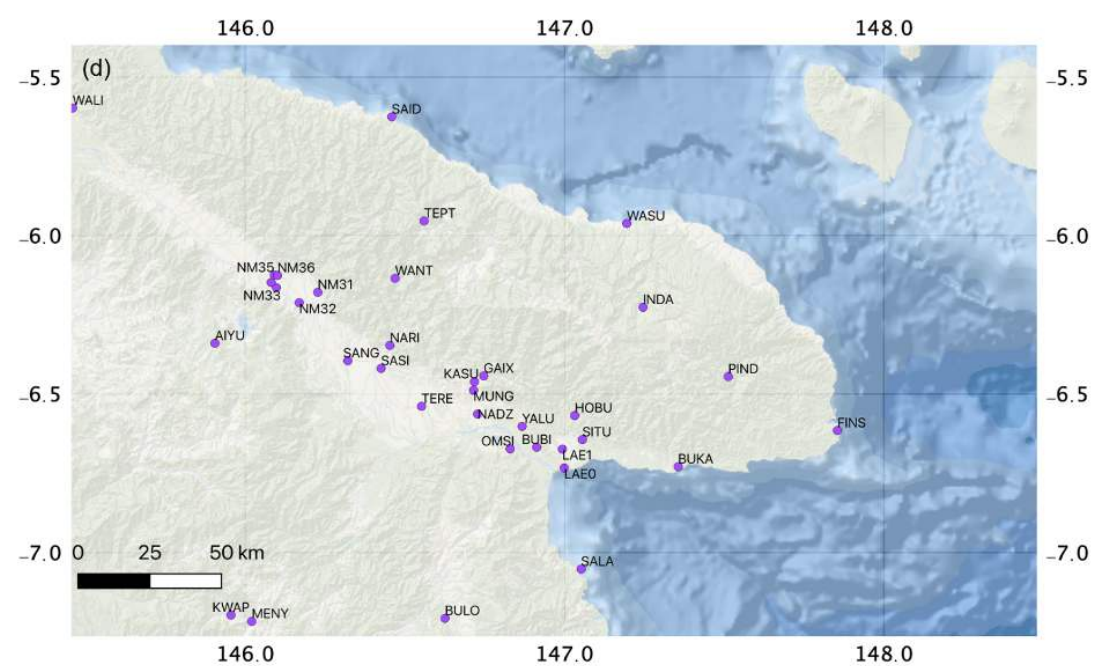
Table B.3: Summary table of the ratio F-test statistics between our best-fit model and alternative models, which indicates the probability of the rejection of the null hypothesis. It verifies the significance of fit improvement when we change the model geometries. The model geometries in different models correspond to the models shown in Figure B.4. Nb.data: number of data; Nb.parm: Number of parameters; DOF: Degree of freedom; χ^2 : The chi-square statistic; F-prob: the probability of rejection of the Null Hypothesis.







(c)



(d)

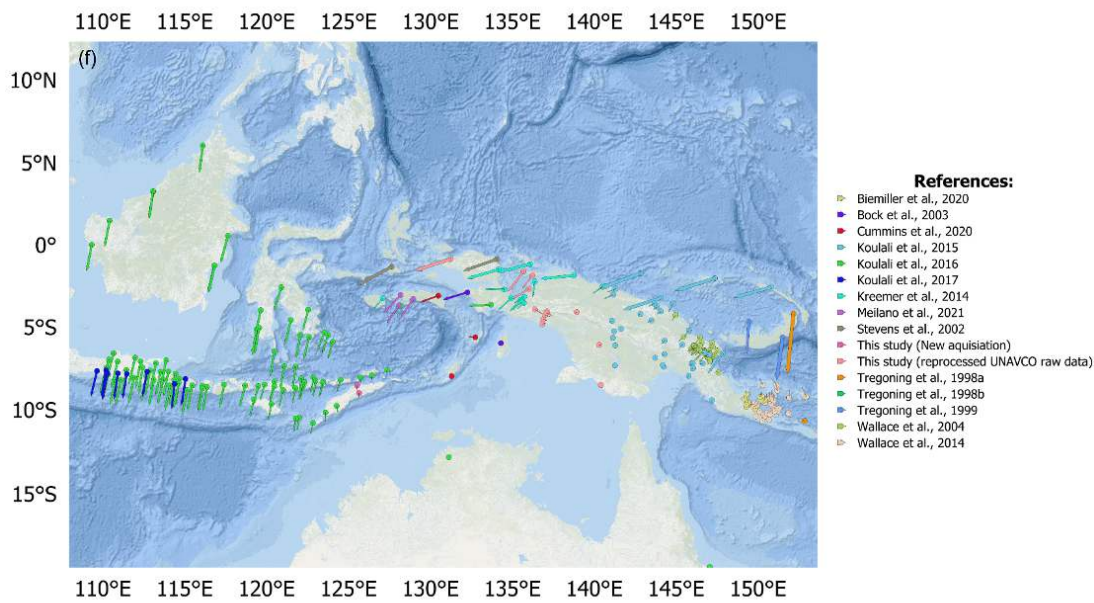
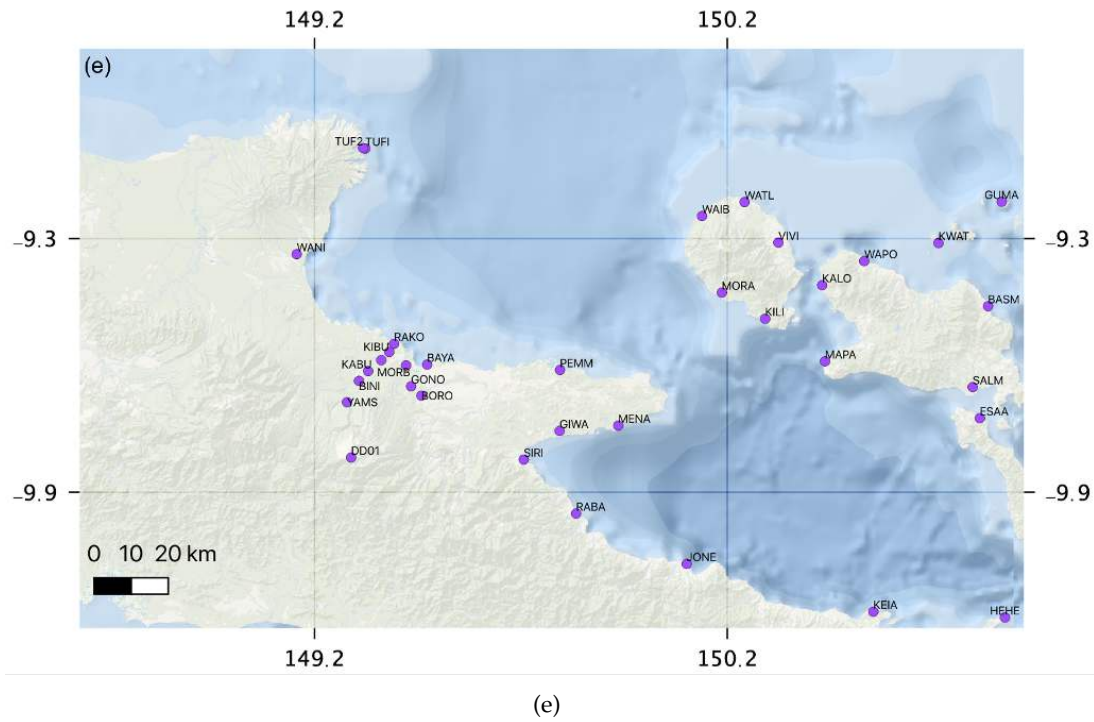
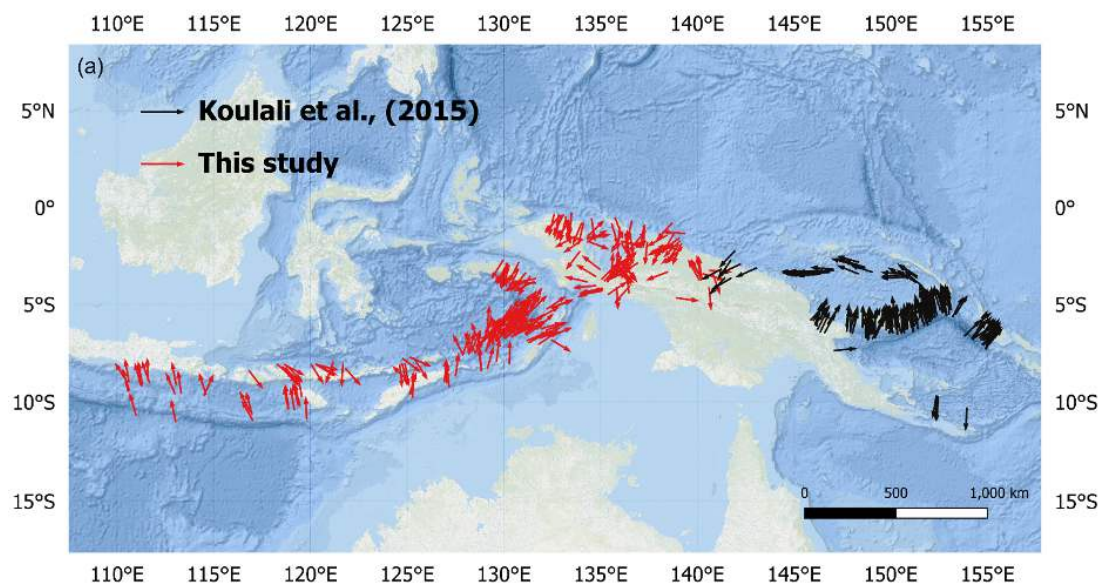
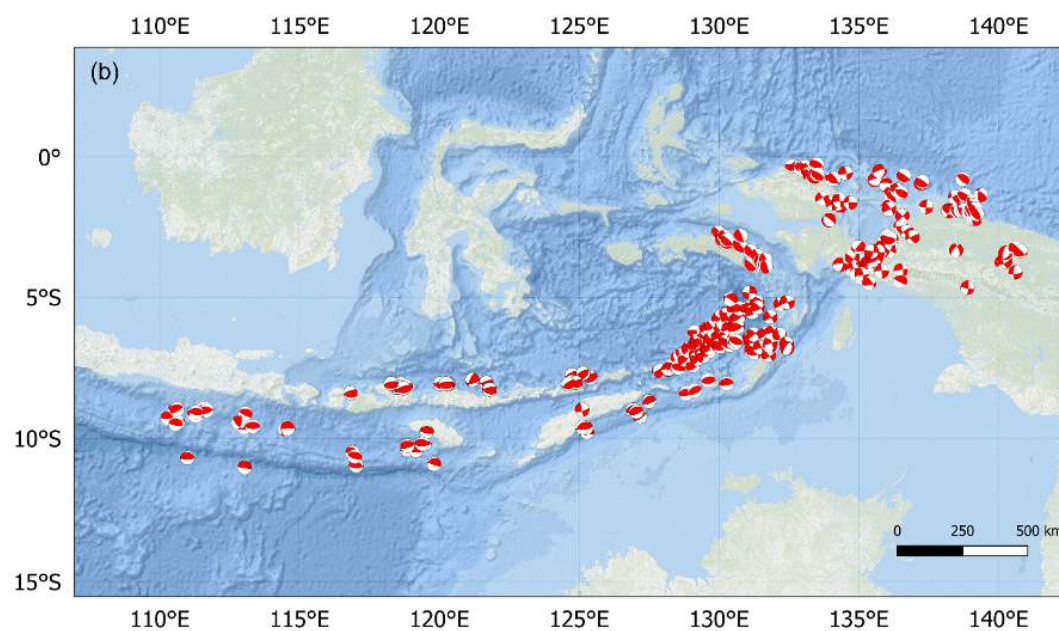


Figure B.2: (a) The locations of the campaign and continuous GPS sites were utilized in this study. Red rectangles represent the area of the zoomed-in view plots shown below in (b), (c), (d), (e), respectively. (f) The references of the GPS velocities used in this study, are identified by the colors.



(a)



(b)

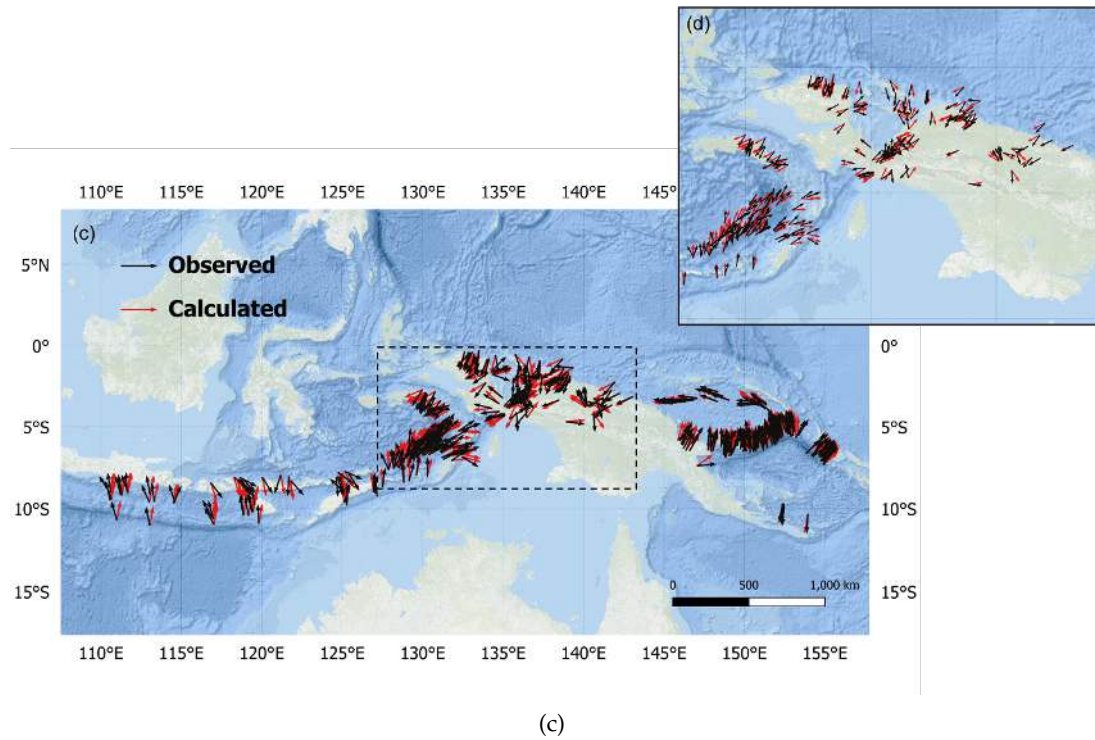


Figure B.3: (a) Earthquake slip vectors azimuths data utilized in the inversion. Red symbols are the new calculated earthquake slip vectors derived from the earthquake focal mechanisms from 1976 to 2018 shown in Figure B.3; Black symbols are the earthquake slip vectors derived from Koulali et al. (2015). The azimuths are clockwise to the north direction. (b) The earthquake focal mechanisms for calculating the slip vectors, which are derived from GCMT catalogue with $M_w \geq 5.5$, depth ≤ 100 km, from Jan1976 to Jan 2018. (c) The modelled (arrows in red) and observed (arrows in black) earthquake slip vectors. (d) The close-up view of the modelled and observed earthquake slip vectors in Western New Guinea and Banda arc region (the area inside the black rectangle).

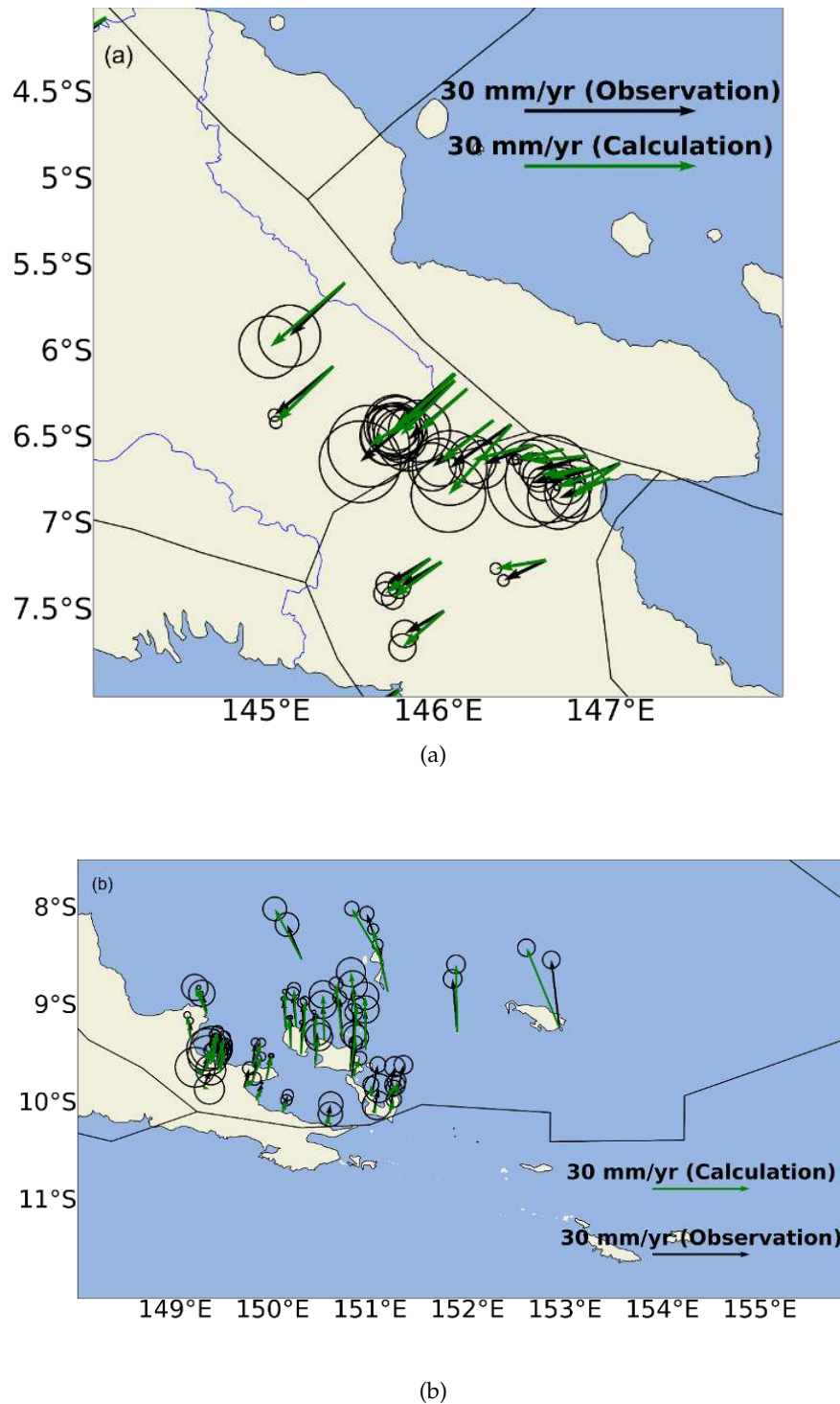


Figure B.4: (a) The zoomed-in view of the observed and calculated GPS velocities in the Ramu-Markham fault zone (upper black rectangle area of Figure B.3a). (b) The zoomed-in view of the observed and calculated GPS velocities in the Woodlark block (lower black rectangle area of Figure B.3a).

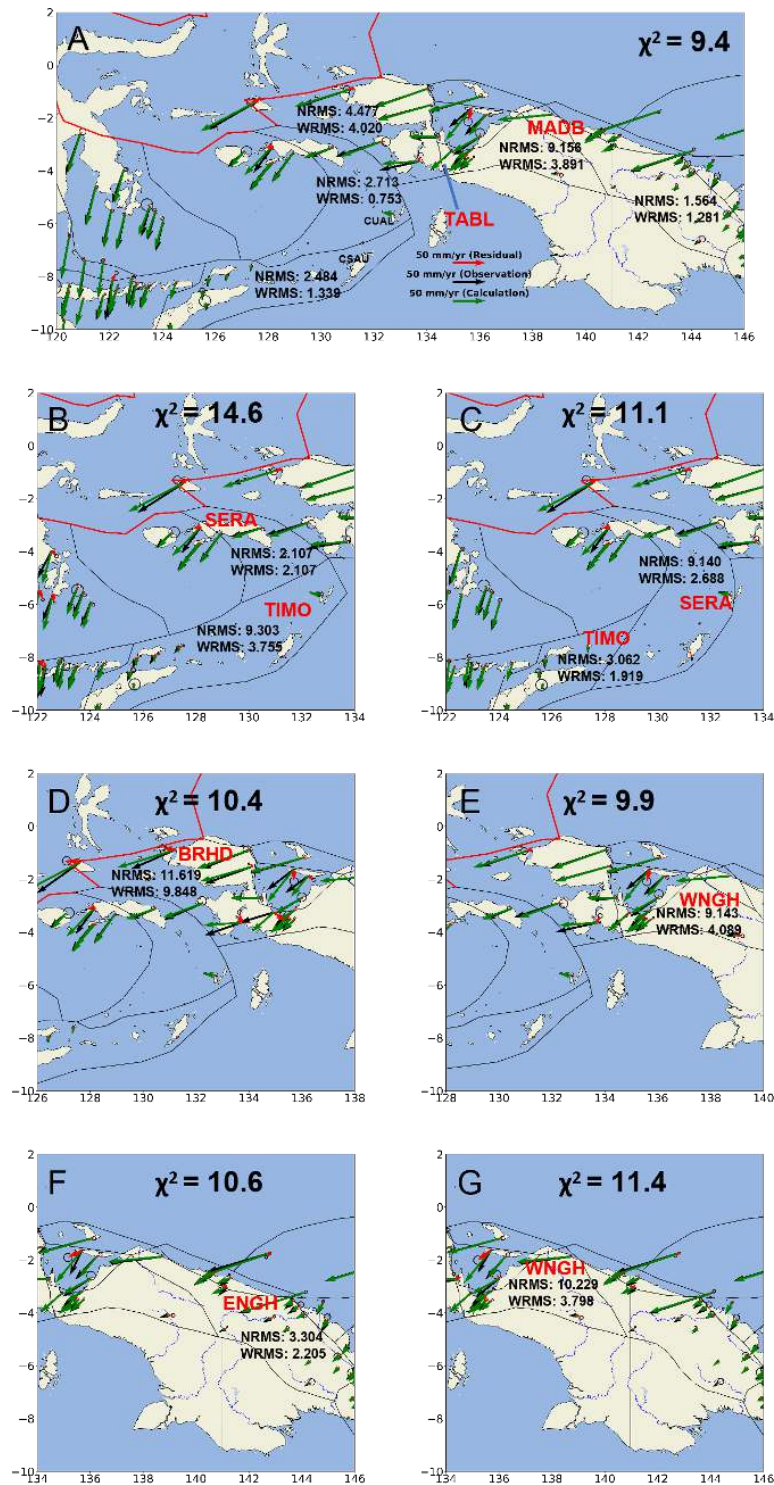


Figure B.5: This figure illustrates our best-fit model (A) and six alternative models (B~G) in different geometrical scenarios.

Figure B.5: The block geometries of the Banda area in Model B and Model C are derived from studies [Koulali et al. \(2016\)](#) and [Cummins et al. \(2020\)](#), respectively. Models D and E illustrate the geometrical scenarios that merge the block [TABL](#) into block [BRHD](#) and [WNGH](#), respectively. Models F and G illustrate the geometrical scenarios that merge the block [MADB](#) into block [HLBL](#) and [ENGH](#), respectively. The [NRMS](#) and [WRMS](#) values for the testing blocks and the χ^2 value for each model are labelled. Black arrows in each model represent the observed [GPS](#) velocities; green arrows in each model represent the calculated [GPS](#) velocities; red arrows with 95% error ellipses show the residuals of the observation and calculation.

Table B.4: Dataset 1.

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
148.980	-35.399	4.880	-3.570	3.620	2.940	-0.010	TIDB
147.056	-19.269	0.110	-0.270	0.300	0.300	0.000	TOW2
133.886	-23.670	0.173	0.199	0.253	0.246	-0.003	ALIC
133.694	-3.645	-55.806	-3.913	1.390	0.865	0.010	KAIM
127.369	-7.590	-0.450	-10.040	0.560	0.530	0.021	ROMA
126.429	-7.935	0.930	-10.990	0.580	0.520	-0.024	WETA
125.739	-8.059	0.890	-12.760	0.500	0.490	-0.003	LIRA
124.517	-8.213	-8.540	-28.190	0.620	0.640	-0.002	CKAL
124.280	-9.776	3.240	-18.150	0.510	0.480	-0.005	KAPA
124.035	-5.905	-11.420	-41.460	1.000	0.920	-0.028	491A
123.753	-5.503	-14.180	-44.170	1.030	0.920	-0.044	D490
123.597	-10.169	-1.280	-23.650	0.500	0.410	-0.002	CKUP
123.539	-5.328	-16.900	-44.330	3.630	3.160	0.014	WNG1
123.473	-8.330	-8.980	-34.390	0.530	0.490	0.005	3032
123.422	-8.371	-9.020	-35.780	0.620	0.570	-0.011	CLWB
123.001	-8.275	-6.200	-38.920	2.480	2.320	0.011	3034
122.868	-8.069	-6.510	-38.180	1.000	0.950	-0.001	CDAI
122.829	-10.807	-5.260	-27.050	0.600	0.550	-0.017	3022
122.599	-5.609	-13.570	-55.060	0.760	0.710	0.034	BBAU
122.545	-3.963	-13.190	-50.910	1.160	1.150	-0.001	CKEN
122.319	-8.348	-10.060	-37.480	0.350	0.350	-0.002	CPBR
122.220	-8.627	-9.160	-32.690	0.390	0.420	-0.010	CMRE
122.110	-8.121	-3.670	-51.860	1.140	1.130	0.000	CKUR
122.075	-5.474	-10.300	-57.820	0.920	0.870	0.026	TLGA
121.988	-10.466	-4.860	-33.770	0.500	0.480	-0.002	3049
121.783	-10.522	-4.900	-33.160	0.500	0.480	-0.001	3050
121.768	-7.406	-7.200	-55.750	1.020	1.000	-0.001	CTOA
121.766	-8.707	-7.140	-36.340	0.570	0.550	-0.021	ENDE

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Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
121.489	-4.582	-13.890	-59.980	0.830	0.700	0.008	TOAR
121.078	-7.382	-9.430	-57.400	0.760	0.660	-0.008	CBON
121.019	-8.821	-10.110	-41.490	0.510	0.480	-0.011	3042
120.905	-2.595	-17.860	-58.650	2.040	1.340	0.022	MLLX
120.490	-8.311	-10.670	-45.490	0.530	0.510	-0.004	CREO
120.482	-6.492	-10.410	-62.110	0.890	0.790	-0.022	APTC
120.478	-8.597	-10.760	-41.350	0.570	0.520	-0.011	RUTE
120.301	-9.669	-7.640	-39.930	0.480	0.470	-0.002	WAIN
119.650	-3.978	-14.240	-65.280	0.560	0.520	-0.010	PARN
119.549	-5.060	-11.390	-65.290	0.470	0.450	0.004	UJPD
119.408	-5.135	-11.610	-64.690	0.640	0.370	-0.003	CMAK
119.219	-9.390	-9.430	-43.570	0.300	0.300	0.000	WAIK
118.693	-8.543	-13.650	-54.540	0.940	0.880	-0.001	BIMA
117.641	0.558	-17.650	-68.010	1.050	0.990	-0.005	TNJB
117.415	-8.489	-10.760	-57.440	0.520	0.490	0.001	3066
117.097	-20.981	-0.640	0.190	0.300	0.300	0.005	KARR
116.840	-1.256	-14.290	-66.880	1.680	1.710	-0.002	CBAL
116.815	-1.272	-15.950	-67.410	1.240	0.850	0.037	BLKP
116.360	-8.635	-9.370	-59.100	5.850	5.140	-0.004	3074
116.112	6.039	-8.660	-68.160	0.350	0.730	0.000	UMSS
116.101	-8.561	-11.800	-60.480	0.680	0.460	-0.007	ANAN
116.076	-8.728	-9.160	-59.430	1.090	1.110	-0.001	CLBR
115.347	-29.047	-0.580	0.220	0.300	0.300	-0.012	YAR2
115.146	-8.818	-11.200	-61.600	0.310	0.300	-0.004	CDNP
114.680	-8.147	-10.600	-64.600	1.080	0.960	0.021	BALI
114.628	-8.393	-11.870	-63.060	0.400	0.350	0.000	CCAK
114.440	-7.838	-11.000	-65.940	1.650	1.580	-0.004	CBRN
114.375	-8.212	-12.150	-63.520	2.290	2.260	0.000	CNYU
114.110	-8.534	-12.420	-62.500	1.860	1.840	0.000	CPES

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Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
114.013	-7.703	-12.430	-62.930	0.590	0.580	-0.005	CSIT
113.875	-7.018	-13.270	-66.190	0.560	0.540	0.000	CSMN
113.693	-8.175	-13.570	-62.700	1.150	1.140	-0.001	CJEM
113.530	-7.719	-11.790	-59.760	1.250	1.260	-0.012	CPAI
113.252	-7.195	-13.650	-66.150	0.560	0.560	-0.001	CSMP
113.115	-8.214	-12.080	-65.600	1.190	1.440	-0.002	CLUM
113.094	3.240	-11.350	-67.100	0.750	0.300	0.000	BIN1
113.067	3.262	-8.640	-67.760	0.390	0.430	-0.008	BINT
112.901	-7.651	-12.620	-61.970	0.550	0.640	-0.001	CPAS
112.663	-7.980	-12.870	-63.580	0.680	0.570	-0.004	CMLG
112.442	-7.466	-10.470	-64.880	0.840	0.760	-0.004	CMJT
112.327	-7.093	-13.250	-65.550	0.570	0.560	-0.001	CLMG
111.986	-6.872	-15.870	-65.590	0.700	0.570	-0.002	CTBN
111.906	-8.066	-12.550	-63.610	0.600	0.550	0.000	CTUL
111.451	-7.606	-11.800	-62.660	0.570	0.520	0.000	CMAG
111.098	-8.196	-12.930	-63.010	0.640	0.580	-0.001	CPAC
110.914	-7.096	-15.990	-65.750	0.740	0.670	-0.004	CPWD
110.799	-8.191	-15.010	-62.480	4.950	4.880	-0.003	SADE
110.667	-6.596	-17.650	-65.430	1.380	1.320	-0.002	CJPR
110.425	1.468	-12.840	-65.650	0.500	0.390	-0.002	UMAS
110.377	-6.987	-16.890	-65.910	0.550	0.550	0.001	CSEM
110.335	-7.893	-14.080	-63.710	6.310	6.250	-0.002	CBTL
110.217	-7.476	-14.750	-64.640	4.540	4.480	-0.001	CMGL
109.329	-0.004	-12.430	-65.770	1.300	1.110	-0.058	CPON
102.105	6.226	-2.280	-57.220	0.980	0.960	-0.005	GETI
98.7150	3.622	-5.020	-50.310	0.660	1.070	0.000	SAMP
96.8340	-12.188	0.150	-0.650	0.420	0.430	-0.005	COCO
72.3700	-7.270	3.170	-0.480	0.530	0.300	-0.001	DGAR
131.133	-12.844	-0.169	0.146	0.305	0.317	0.000	DARW

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Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
119.492	-8.589	-12.190	-48.080	3.720	1.340	0.012	KOMO
119.880	-8.489	-11.120	-40.260	4.870	1.740	0.054	LABU
103.680	1.346	-5.970	-56.770	1.730	0.940	-0.002	NTUS
135.712	-3.541	-16.841	-15.587	0.560	0.520	0.053	64KM
136.841	-4.829	8.960	1.700	2.530	2.230	0.000	AMAR
134.312	-5.987	4.737	3.103	2.500	0.600	0.096	ARUX
140.414	-8.518	1.110	1.080	1.000	0.770	0.000	BUKE
136.098	-1.175	-81.866	-23.309	1.177	0.547	0.007	BIAK
135.505	-3.367	-26.794	-27.685	0.430	0.350	0.054	CNAB
115.471	-8.543	-12.212	-62.309	0.630	0.560	0.016	CPBI
132.265	-2.900	-59.879	-22.507	2.700	1.300	0.017	FAKF
137.114	-4.068	9.960	-8.840	2.030	1.590	0.000	KIMG
135.730	-3.176	-25.553	-15.925	0.340	0.280	0.014	LEGA
134.050	-0.886	-79.995	-28.623	1.777	0.860	0.006	MANO
137.118	-4.045	12.390	-12.380	1.820	1.680	0.000	NORA
127.644	-1.341	-87.684	-46.768	2.600	0.700	0.011	OBIX
135.692	-1.629	-38.980	-49.680	2.540	2.010	0.000	POM2
134.169	-1.506	-80.169	-23.439	0.540	0.500	-0.036	RANS
140.516	-2.556	-22.756	-17.162	1.207	0.507	0.008	SENT
131.254	-0.875	-89.494	-28.511	2.195	1.113	-0.026	SORO
138.752	-1.872	-82.581	-8.147	0.280	0.230	-0.012	SRMI
136.381	-3.927	17.300	-11.070	1.530	1.270	0.000	TALI
136.895	-4.534	8.820	-3.420	0.890	0.730	0.000	TIMI
140.301	-6.099	5.210	1.000	1.480	1.140	0.000	TNMH
135.588	-3.487	-24.948	-20.204	0.500	0.440	0.016	TOPO
137.009	-4.285	13.450	-4.660	1.750	1.420	0.000	TP50
137.092	-4.145	6.990	-3.750	2.850	2.510	0.000	TPRA
138.950	-4.096	-5.218	-3.922	1.063	0.537	0.017	WAMB
136.019	-2.696	-41.040	-24.030	2.730	2.290	0.000	WAPO

Continued on next page

Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
134.508	-2.728	-47.720	1.041	0.980	0.790	-0.009	WASI
136.240	-1.874	-25.320	-32.090	1.160	0.880	0.000	YAPE
134.945	-3.248	-32.736	-29.977	0.740	0.600	0.022	YAU
159.800	-11.303	-2.449	-3.658	4.200	1.800	0.000	BELL
155.463	-4.783	-97.731	-33.189	4.600	2.400	0.000	CART
160.053	-9.428	-71.454	-15.519	2.700	2.500	0.000	HONI
161.903	-10.452	-77.486	-20.472	5.000	3.900	0.000	KIRA
152.833	-10.688	-5.134	3.903	2.700	1.500	0.000	MISI
154.675	-3.335	-102.34	-33.563	4.600	2.400	0.000	NUGU
142.837	-1.730	-103.60	-35.895	0.915	0.880	0.000	WUVU
142.825	-4.219	-5.810	-2.950	0.880	0.830	0.004	ABTI
141.267	-7.348	0.020	-0.290	0.330	0.290	0.011	AIAM
145.905	-6.340	-8.410	-6.560	2.900	1.900	0.052	AIYU
143.500	-4.606	-9.560	-4.990	0.840	0.780	-0.011	AMBN
144.073	-4.058	-11.230	-7.630	1.880	1.700	0.002	ANGR
140.704	-2.515	-22.190	-10.580	0.550	0.540	0.001	ANGS
144.820	-3.598	-10.380	-19.500	0.890	0.850	0.002	BAMI
141.167	-3.023	-22.640	-11.500	1.360	1.310	0.007	BEWA
144.968	-4.295	-8.890	-13.420	1.900	1.600	-0.005	BOGI
146.913	-6.668	-8.880	-1.760	1.200	1.000	0.013	BUBI
147.356	-6.729	-10.210	-24.020	1.500	1.300	0.011	BUKA
146.626	-7.207	-7.930	-1.870	0.400	0.370	0.009	BULO
147.855	-6.615	-36.480	-48.760	1.980	1.760	-0.015	FINS
146.747	-6.443	-25.780	-25.210	1.600	1.400	-0.005	GAIX
143.723	-6.879	-1.110	-0.640	1.180	1.060	0.124	GOB1
145.392	-6.081	-9.180	-10.180	0.430	0.420	0.003	GOKA
144.307	-5.832	-8.150	-7.360	0.400	0.380	-0.002	HGEN
147.032	-6.568	-26.010	-22.320	1.300	1.100	-0.003	HOB
147.246	-6.226	-20.010	-31.150	1.700	1.400	-0.008	INDA

Continued on next page

Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
151.505	-5.645	-14.830	-107.27	3.000	1.200	0.000	JACQ
146.034	-7.501	-6.450	-6.770	0.960	0.910	0.002	KAIN
146.718	-6.461	-18.580	-19.820	1.900	1.300	-0.034	KASU
150.807	-2.582	-97.462	-24.776	1.825	1.315	0.018	KAVI
145.772	-7.958	-3.610	-5.920	0.850	0.800	-0.021	KERE
144.249	-7.424	-0.320	-1.550	0.560	0.450	0.044	KIKO
141.278	-6.127	1.210	0.240	0.660	0.580	-0.021	KIUN
144.186	-7.322	0.120	-0.980	1.130	0.950	-0.002	KOPB
145.955	-7.197	-7.010	-6.520	0.830	0.790	0.002	KWAP
146.999	-6.733	-5.250	-2.630	2.200	1.400	-0.045	LAE0
146.993	-6.674	-8.320	-3.750	0.200	0.230	0.018	LAE1
145.782	-5.212	-11.400	-16.730	0.850	0.810	-0.002	MAD1
146.020	-7.217	-7.700	-6.670	0.800	0.780	0.001	MENY
147.187	-9.434	-2.790	-3.290	0.360	0.350	0.008	MORE
147.579	-7.771	-5.570	2.950	2.700	1.700	0.028	MORX
146.715	-6.488	-19.470	-18.820	1.400	1.200	0.004	MUNG
146.728	-6.563	-7.270	-2.160	0.340	0.320	0.009	NADZ
146.453	-6.347	-21.550	-15.700	5.100	2.800	0.051	NARI
141.142	-5.667	0.260	-0.840	1.010	0.550	0.013	NING
146.227	-6.179	-18.640	-17.360	2.300	1.400	0.040	NM31
146.169	-6.212	-7.530	-7.780	2.200	1.500	0.033	NM32
146.097	-6.164	-8.660	-10.000	1.900	1.400	0.047	NM33
146.081	-6.148	-8.860	-8.910	1.700	1.300	0.012	NM34
146.091	-6.125	-9.970	-11.000	2.200	1.400	0.036	NM35
146.101	-6.126	-10.670	-11.200	2.100	1.400	0.021	NM36
146.830	-6.673	-4.790	-2.280	3.100	1.600	0.022	OMSI
147.513	-6.445	-23.900	-35.370	1.600	1.200	0.010	PIND
147.366	-2.043	-98.520	-31.430	0.340	0.430	0.006	PNGM
146.459	-5.625	-15.710	-23.400	2.300	1.700	0.026	SAID

Continued on next page

Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
147.052	-7.052	-11.720	4.480	3.600	2.000	-0.024	SALA
146.321	-6.395	-8.550	-7.740	1.700	1.400	0.019	SANG
146.425	-6.419	-10.160	-12.670	2.650	2.360	0.005	SASI
147.056	-6.644	-7.870	-6.510	1.400	1.100	-0.003	SITU
141.220	-5.258	0.210	0.450	0.670	0.580	-0.008	TABU
144.076	-3.239	-94.690	-30.310	0.910	0.860	-0.004	TARO
141.643	-5.126	-1.880	-0.700	1.120	1.070	-0.001	TELE
146.560	-5.954	-21.880	-23.470	3.500	2.600	0.018	TEPT
146.552	-6.539	-9.770	-2.970	1.700	1.400	-0.016	TERE
143.836	-3.792	-9.640	-6.770	1.840	1.680	-0.004	TRNG
141.304	-2.685	-19.890	-8.230	0.470	0.460	-0.001	VANI
145.459	-5.597	-12.220	-11.590	2.200	1.700	0.018	WALI
146.469	-6.135	-23.430	-22.790	1.600	1.300	0.002	WANT
147.195	-5.962	-19.820	-37.370	1.800	1.300	0.003	WASU
143.667	-3.584	-14.420	-6.500	0.560	0.510	0.001	WEWK
149.435	-4.688	-4.510	-79.230	2.000	0.800	0.000	WITU
144.294	-6.659	-3.920	-3.810	1.880	1.840	0.026	WOPA
146.867	-6.602	-9.210	-1.370	1.200	1.000	-0.005	YALU
141.096	-4.629	-5.220	-0.630	0.500	0.460	-0.001	YAPS
200.335	22.126	-117.80	14.220	0.940	0.960	0.000	KOKB
204.544	19.801	-115.08	19.060	0.720	0.200	0.000	MKEA
127.099	-3.271	-21.190	-24.275	3.360	2.790	-0.068	NAML
159.954	-9.435	-65.684	-14.500	0.896	0.962	0.000	SOLO
125.528	-8.549	-0.600	-13.270	1.510	1.520	0.003	DILI
125.653	-9.002	-0.190	-10.540	3.510	2.880	-0.022	SAME
131.298	-7.984	-2.330	-1.840	0.300	0.400	0.000	CSAU
132.745	-5.632	-17.960	1.950	0.200	0.200	0.000	CUAL
128.185	-3.696	-28.260	-33.600	0.300	0.300	0.000	CAMB
130.488	-3.104	-44.820	-16.120	1.000	1.000	0.000	CBLA

Continued on next page

Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
150.337	-10.310	0.820	1.080	0.520	0.990	0.000	ALT2
150.832	-9.465	1.770	13.910	1.110	1.380	0.000	BASM
149.473	-9.608	1.350	5.550	0.830	0.580	0.000	BAYA
151.185	-9.940	2.890	3.370	1.270	1.090	0.000	BWAR
150.426	-10.407	1.550	2.040	0.930	0.830	0.000	DAIO
151.015	-9.927	0.580	3.180	0.990	1.190	0.000	DARB
151.204	-10.100	1.980	3.710	0.960	1.140	0.000	DIGA
150.812	-9.739	3.330	5.650	0.840	0.800	0.000	ESAA
149.794	-9.770	3.510	7.070	0.550	1.060	0.000	GIWA
152.944	-9.225	-9.400	24.210	1.090	0.460	0.000	GUA1
150.865	-9.210	-1.040	16.250	1.810	1.810	0.000	GUMA
150.873	-10.226	1.600	3.340	1.290	0.950	0.000	HEHE
150.102	-10.095	1.950	3.400	0.700	0.920	0.000	JONE
150.299	-8.522	-7.510	15.140	1.480	1.240	0.000	KAWA
150.554	-10.212	1.940	2.620	1.520	1.030	0.000	KEIA
151.036	-10.100	1.740	1.980	1.800	0.690	0.000	KURA
151.274	-9.923	0.730	4.110	1.160	0.680	0.000	KWAN
150.712	-9.311	-1.040	15.720	0.850	0.850	0.000	KWAT
150.728	-10.302	1.160	0.360	0.800	1.470	0.000	LELE
151.125	-8.535	-8.590	15.600	0.890	0.290	0.000	LOS2
150.437	-9.600	1.920	7.980	1.720	1.160	0.000	MAPA
149.936	-9.757	2.440	6.930	0.270	1.580	0.000	MENA
149.866	-10.398	1.220	0.680	0.490	0.570	0.000	NUBE
149.795	-9.621	3.440	6.910	0.540	0.680	0.000	PEMM
150.795	-9.663	2.630	9.860	1.560	0.900	0.000	SALM
150.268	-10.683	0.710	1.650	0.950	0.650	0.000	SIBA
149.707	-9.840	3.990	2.390	0.830	2.280	0.000	SIRI
150.662	-10.613	0.480	1.620	0.450	0.690	0.000	SMRI
151.867	-10.225	2.590	4.200	0.850	0.480	0.000	STRA

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Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
149.323	-9.080	-2.870	7.690	1.640	1.130	0.000	TUFI
150.953	-9.452	0.660	16.210	1.720	1.640	0.000	UAMA
151.183	-8.853	-3.740	18.800	0.680	0.610	0.000	VAKU
150.324	-9.310	1.010	10.360	0.580	0.480	0.000	VIVI
150.532	-9.355	0.360	13.770	1.720	2.100	0.000	WAPO
150.242	-9.211	0.110	11.070	0.830	0.460	0.000	WATL
151.896	-9.271	0.390	20.480	1.160	1.080	0.000	YANA
149.308	-9.648	2.840	6.040	0.730	0.610	0.000	BINI
149.459	-9.684	2.270	5.500	0.780	0.640	0.000	BORO
149.289	-9.835	2.650	-1.000	1.880	1.600	0.000	DD01
149.434	-9.661	3.410	5.870	0.680	0.560	0.000	GONO
149.362	-9.597	2.330	7.540	0.610	0.510	0.000	GOUR
149.330	-9.624	0.890	4.860	2.640	2.050	0.000	KABU
150.430	-9.414	1.260	8.840	0.240	0.220	0.000	KALO
149.381	-9.577	1.530	8.030	0.680	0.570	0.000	KIBU
150.292	-9.496	1.650	8.790	0.260	0.230	0.000	KILI
150.187	-9.432	0.200	8.950	0.240	0.220	0.000	MORA
149.422	-9.610	3.210	8.160	0.790	0.630	0.000	MORB
149.834	-9.972	2.340	3.460	0.120	0.100	0.000	RABA
149.393	-9.557	2.050	8.360	0.750	0.610	0.000	RAKO
149.318	-9.079	-1.520	7.650	0.250	0.230	0.000	TUF2
150.139	-9.245	0.320	11.400	0.260	0.240	0.000	WAIB
149.157	-9.338	-0.180	6.930	0.420	0.350	0.000	WANI
149.279	-9.700	-1.410	1.690	2.500	2.180	0.000	YAMS
109.653	-7.670	-15.270	-64.020	0.740	0.670	-0.001	CKBM
110.208	-7.635	-11.630	-64.160	0.940	0.720	0.012	BUTU
110.295	-7.817	-13.420	-66.670	1.350	1.320	0.002	JOGS
110.926	-7.814	-9.350	-64.690	1.550	1.230	-0.085	WGIR
111.475	-7.847	-10.690	-62.320	1.260	1.070	-0.032	PONO

Continued on next page

Table B.4 – continued from previous page

Lon (deg)	Lat (deg)	Ve (mm/yr)	Vn (mm/yr)	Sige (mm/yr)	Sign (mm/yr)	Rho -	Sites -
112.714	-7.710	-11.530	-62.580	1.620	1.220	-0.058	SKOR
115.058	-8.150	-10.220	-66.530	0.420	0.410	-0.006	CSRJ
114.389	-8.451	-7.200	-62.770	1.830	2.020	0.003	CMCR
128.080	-3.710	-29.330	-42.590	0.300	0.260	0.000	AMB1
128.190	-3.060	-42.870	-44.790	0.490	0.360	0.000	PIRU
128.960	-3.300	-31.730	-46.330	0.290	0.220	0.000	MSHI
136.380	-2.241	-5.666	-38.783	3.150	2.530	0.005	WREN

Table B.5: Dataset 2.

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
, 152.02	-5.20	342.50	20.00
150.78	-6.32	347.80	20.00
152.14	-5.59	348.10	20.00
152.33	-5.40	345.10	20.00
149.19	-6.54	359.80	20.00
153.02	-5.55	359.40	20.00
151.17	-6.47	358.30	20.00
151.70	-5.59	357.70	20.00
150.12	-6.51	347.90	20.00
152.89	-5.08	344.90	20.00
151.92	-5.65	347.40	20.00
151.94	-6.12	340.80	20.00
151.97	-5.59	348.20	20.00
153.04	-5.29	354.20	20.00
152.82	-5.43	350.00	20.00
153.03	-5.18	344.30	20.00
153.00	-5.14	350.90	20.00
152.91	-5.58	348.90	20.00
149.03	-6.27	353.30	20.00
148.81	-6.86	353.30	20.00
148.83	-6.86	359.00	20.00
148.98	-6.49	354.00	20.00
151.13	-6.03	345.50	20.00
152.69	-5.31	343.80	20.00
152.34	-5.26	348.10	20.00
152.20	-5.70	343.80	20.00
153.13	-5.30	350.10	20.00
151.94	-5.46	357.00	20.00

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Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
150.33	-6.27	350.50	20.00
151.14	-6.33	342.00	20.00
150.04	-6.37	346.40	20.00
152.31	-5.69	344.60	20.00
151.96	-5.68	342.50	20.00
152.00	-5.90	348.60	20.00
152.69	-5.46	349.10	20.00
151.66	-5.93	347.50	20.00
152.15	-5.74	343.50	20.00
152.08	-5.72	340.20	20.00
151.36	-5.99	354.40	20.00
150.52	-6.43	346.60	20.00
150.62	-6.43	356.60	20.00
152.75	-5.42	352.20	20.00
150.33	-6.22	356.20	20.00
150.76	-6.33	355.90	20.00
150.80	-6.26	356.60	20.00
150.03	-6.47	345.50	20.00
151.74	-6.12	344.70	20.00
150.34	-6.59	359.50	20.00
152.12	-5.59	350.00	20.00
151.85	-6.01	344.70	20.00
110.55	-9.01	-33.20	20.00
110.57	-9.49	-12.20	20.00
110.62	-8.98	-10.00	20.00
110.65	-9.43	-20.50	20.00
110.99	-10.69	-16.40	20.00
111.23	-9.16	-15.10	20.00
111.30	-9.20	-11.10	20.00

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Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
111.31	-9.09	-11.00	20.00
111.60	-8.95	-1.80	20.00
111.68	-9.02	-20.00	20.00
113.01	-9.61	-23.80	20.00
113.04	-11.03	-12.00	20.00
113.06	-9.13	-11.20	20.00
113.32	-9.58	-8.30	20.00
114.49	-9.68	24.60	20.00
114.60	-9.65	-17.20	20.00
116.90	-10.51	-28.60	20.00
116.98	-10.64	-14.70	20.00
117.03	-10.96	-29.20	20.00
118.86	-10.41	-10.90	20.00
118.86	-10.27	-8.00	20.00
119.17	-10.43	-9.50	20.00
119.38	-10.20	-14.20	20.00
119.46	-10.21	-13.80	20.00
119.55	-9.77	-9.00	20.00
119.81	-10.91	-2.50	20.00
125.11	-8.99	-46.30	20.00
125.12	-9.62	17.50	20.00
125.24	-9.64	4.00	20.00
125.28	-9.79	3.20	20.00
126.93	-9.00	4.00	20.00
127.05	-9.07	0.30	20.00
127.18	-9.24	-6.70	20.00
127.50	-8.70	7.60	20.00
128.19	-7.58	-4.80	20.00
128.83	-8.42	-5.90	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
129.14	-8.32	15.80	20.00
129.61	-7.96	7.80	20.00
116.82	-8.40	142.60	20.00
118.27	-8.07	129.90	20.00
118.47	-8.21	136.00	20.00
118.53	-8.20	129.00	20.00
118.63	-8.08	118.40	20.00
118.72	-8.23	145.50	20.00
118.80	-8.16	137.00	20.00
120.03	-8.07	148.10	20.00
120.25	-8.07	121.20	20.00
120.30	-8.09	104.60	20.00
120.32	-8.09	117.80	20.00
121.18	-7.94	-161.40	20.00
121.68	-8.04	-176.80	20.00
121.80	-8.28	138.40	20.00
124.62	-8.08	174.50	20.00
124.73	-8.02	166.70	20.00
124.74	-7.76	127.30	20.00
124.88	-8.04	169.60	20.00
125.14	-7.71	114.00	20.00
125.41	-7.86	147.60	20.00
134.33	-3.85	-77.30	20.00
134.78	-4.03	-96.40	20.00
134.93	-4.17	-112.40	20.00
135.10	-4.18	-102.30	20.00
135.11	-4.31	-99.40	20.00
135.13	-4.23	-98.30	20.00
135.82	-4.09	175.80	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
136.51	-4.05	-139.00	20.00
132.61	-0.33	-166.40	20.00
132.83	-0.38	-170.40	20.00
132.91	-0.39	-141.60	20.00
132.92	-0.42	-136.60	20.00
132.97	-0.40	-163.10	20.00
133.09	-0.36	-152.60	20.00
133.18	-0.47	170.40	20.00
133.20	-0.61	-165.80	20.00
133.27	-0.70	171.70	20.00
133.30	-0.64	176.10	20.00
133.38	-0.75	-143.70	20.00
133.48	-0.58	-169.10	20.00
133.50	-0.26	-174.90	20.00
133.53	-0.63	-138.10	20.00
134.03	-0.79	-157.60	20.00
134.12	-0.78	-167.00	20.00
134.27	-1.62	79.90	20.00
134.30	-1.79	59.50	20.00
134.31	-1.74	110.60	20.00
134.32	-1.51	45.70	20.00
134.33	-1.57	81.80	20.00
134.53	-0.57	171.10	20.00
133.70	-1.49	-118.70	20.00
133.94	-2.26	-142.70	20.00
134.07	-1.66	-125.00	20.00
135.45	-3.34	105.00	20.00
135.46	-3.38	103.90	20.00
135.78	-3.19	126.90	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
135.83	-3.22	43.10	20.00
135.91	-3.05	144.80	20.00
136.02	-2.82	136.40	20.00
136.05	-3.17	42.70	20.00
136.06	-2.85	140.10	20.00
136.08	-3.36	22.90	20.00
136.16	-2.93	141.80	20.00
136.50	-2.49	-8.50	20.00
136.56	-2.10	41.80	20.00
138.21	-1.91	-153.60	20.00
138.23	-1.94	-151.90	20.00
138.45	-1.43	-119.30	20.00
138.50	-1.91	-118.50	20.00
138.64	-1.91	-114.70	20.00
138.72	-0.79	-136.90	20.00
138.76	-1.91	-122.00	20.00
138.79	-1.36	-150.00	20.00
138.93	-1.97	-102.20	20.00
139.05	-1.90	-146.10	20.00
139.07	-1.58	-125.80	20.00
139.10	-2.20	-126.80	20.00
139.11	-1.72	-135.30	20.00
139.18	-2.21	-80.20	20.00
139.18	-1.85	-157.90	20.00
139.23	-2.04	-135.90	20.00
139.38	-1.36	-84.80	20.00
138.49	-3.33	-110.50	20.00
140.12	-3.77	-29.70	20.00
140.19	-3.67	-10.40	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
140.23	-3.73	-7.00	20.00
140.23	-3.74	-26.70	20.00
140.25	-3.72	-32.10	20.00
134.77	-3.58	-58.50	20.00
134.99	-3.22	-52.50	20.00
135.04	-3.73	44.20	20.00
135.18	-3.82	42.60	20.00
135.31	-3.79	62.50	20.00
135.35	-3.86	34.10	20.00
135.40	-3.72	52.30	20.00
135.49	-3.56	30.10	20.00
135.49	-3.65	29.40	20.00
135.53	-3.62	51.30	20.00
135.53	-3.70	62.90	20.00
135.54	-3.55	5.00	20.00
135.57	-3.60	37.10	20.00
135.60	-3.65	61.70	20.00
135.65	-3.57	49.70	20.00
135.77	-3.38	7.60	20.00
135.38	-4.50	56.10	20.00
136.48	-4.43	-9.10	20.00
136.73	-2.67	-147.10	20.00
136.93	-2.86	-123.30	20.00
138.89	-4.67	97.30	20.00
140.26	-3.42	105.90	20.00
140.61	-4.12	175.20	20.00
140.61	-3.26	93.70	20.00
140.79	-3.37	161.20	20.00
127.87	-7.63	18.20	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
127.90	-7.62	-26.50	20.00
128.19	-7.58	13.60	20.00
128.32	-7.44	21.70	20.00
128.51	-7.51	31.50	20.00
128.53	-7.50	-29.00	20.00
128.53	-7.15	55.20	20.00
128.55	-7.51	11.70	20.00
128.62	-7.07	54.00	20.00
128.75	-7.05	-21.60	20.00
128.78	-7.22	22.60	20.00
128.92	-6.83	54.50	20.00
128.95	-6.94	19.60	20.00
128.99	-6.84	52.60	20.00
129.07	-7.43	15.90	20.00
129.11	-6.72	33.40	20.00
129.13	-6.25	5.80	20.00
129.18	-7.05	44.10	20.00
129.20	-6.55	53.80	20.00
129.21	-7.19	17.70	20.00
129.24	-6.62	48.30	20.00
129.30	-6.76	61.30	20.00
129.39	-6.63	41.50	20.00
129.39	-6.97	7.00	20.00
129.44	-7.09	5.20	20.00
129.46	-6.24	57.00	20.00
129.57	-6.85	22.70	20.00
129.60	-6.86	16.30	20.00
129.63	-6.09	56.00	20.00
129.63	-6.69	-16.10	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
129.65	-6.80	52.40	20.00
129.65	-6.93	6.20	20.00
129.67	-6.82	35.30	20.00
129.68	-6.51	58.60	20.00
129.74	-6.07	56.70	20.00
129.83	-6.65	38.80	20.00
129.98	-6.40	29.80	20.00
129.98	-2.70	-147.80	20.00
129.99	-6.54	38.10	20.00
129.99	-6.73	32.90	20.00
130.00	-5.76	61.40	20.00
130.06	-6.76	50.70	20.00
130.09	-5.69	37.50	20.00
130.09	-6.30	24.00	20.00
130.10	-6.07	45.50	20.00
130.13	-2.88	-179.30	20.00
130.14	-3.01	-163.90	20.00
130.21	-2.86	-150.80	20.00
130.23	-6.41	37.80	20.00
130.24	-6.58	36.80	20.00
130.26	-5.58	45.90	20.00
130.27	-3.08	-161.10	20.00
130.27	-2.97	-141.00	20.00
130.30	-6.62	6.30	20.00
130.30	-2.97	-146.80	20.00
130.34	-5.78	69.10	20.00
130.36	-6.10	46.40	20.00
130.38	-6.71	49.80	20.00
130.41	-5.08	-145.20	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
130.51	-6.63	55.50	20.00
130.52	-6.60	64.60	20.00
130.54	-6.50	6.70	20.00
130.55	-5.40	56.60	20.00
130.55	-6.03	77.10	20.00
130.57	-6.10	45.10	20.00
130.59	-6.63	32.50	20.00
130.60	-5.82	35.40	20.00
130.62	-6.56	24.90	20.00
130.68	-6.06	27.70	20.00
130.72	-5.68	29.70	20.00
130.73	-5.41	37.20	20.00
130.73	-3.16	-137.10	20.00
130.76	-3.19	-153.70	20.00
130.78	-2.82	-153.30	20.00
131.03	-5.41	32.50	20.00
131.10	-4.84	-174.30	20.00
131.13	-3.37	-142.40	20.00
131.14	-3.83	-114.20	20.00
131.17	-5.33	26.10	20.00
131.20	-5.53	35.30	20.00
131.37	-5.18	30.10	20.00
131.37	-3.53	-149.10	20.00
131.38	-5.37	45.70	20.00
131.46	-3.72	-100.50	20.00
131.59	-3.82	-115.60	20.00
131.65	-3.67	-101.90	20.00
131.68	-3.91	-88.30	20.00
128.83	-8.42	-3.80	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
130.28	-8.07	1.60	20.00
131.08	-6.49	56.90	20.00
131.10	-6.54	38.30	20.00
131.14	-6.59	55.50	20.00
131.17	-6.88	66.90	20.00
131.18	-6.88	66.70	20.00
131.24	-6.33	44.70	20.00
131.28	-6.98	60.90	20.00
131.45	-6.80	68.30	20.00
131.47	-6.79	71.80	20.00
131.69	-6.30	46.60	20.00
131.78	-7.07	55.60	20.00
131.82	-6.74	73.10	20.00
131.84	-5.71	59.70	20.00
131.85	-6.62	68.20	20.00
131.88	-6.27	74.10	20.00
132.17	-6.34	69.40	20.00
132.21	-5.25	56.60	20.00
132.42	-6.65	67.50	20.00
132.43	-5.18	71.50	20.00
132.44	-6.82	121.00	20.00
132.46	-5.18	68.90	20.00
135.57	-0.82	163.40	20.00
135.74	-0.51	159.10	20.00
135.99	-1.01	-174.50	20.00
136.04	-1.73	106.50	20.00
136.06	-1.78	98.40	20.00
136.09	-1.86	150.30	20.00
136.14	-1.31	-150.10	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
136.27	-1.36	172.20	20.00
136.38	-1.19	-175.80	20.00
136.51	-1.28	171.30	20.00
136.62	-0.67	-166.90	20.00
137.23	-0.97	-172.10	20.00
137.28	-0.89	-177.10	20.00
137.42	-1.78	-174.00	20.00
142.25	-2.92	244.80	20.00
141.95	-2.23	222.80	20.00
141.75	-2.72	214.90	20.00
142.71	-3.29	229.00	20.00
143.38	-3.27	248.30	20.00
143.09	-2.82	238.00	20.00
143.09	-3.12	246.30	20.00
141.71	-2.80	210.50	20.00
141.77	-3.64	239.50	20.00
141.44	-3.62	222.40	20.00
141.27	-3.17	241.50	20.00
146.37	-4.55	342.00	20.00
146.61	-4.32	338.70	20.00
146.81	-4.09	340.10	20.00
146.85	-3.32	254.90	20.00
147.08	-3.24	265.00	20.00
145.85	-3.25	273.00	20.00
147.01	-3.34	268.90	20.00
145.95	-3.46	269.30	20.00
146.80	-3.35	267.60	20.00
145.13	-3.41	266.60	20.00
146.58	-3.37	265.40	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
147.04	-3.20	275.10	20.00
146.18	-3.33	267.40	20.00
146.47	-3.26	261.90	20.00
146.85	-3.32	264.60	20.00
145.82	-3.36	263.90	20.00
148.35	-3.44	291.60	20.00
148.37	-2.84	286.10	20.00
148.69	-3.10	287.70	20.00
148.61	-3.17	292.40	20.00
148.08	-2.95	285.00	20.00
149.07	-3.35	287.50	20.00
148.67	-3.20	293.10	20.00
148.38	-3.06	291.10	20.00
150.68	-3.49	266.40	20.00
150.92	-3.69	298.50	20.00
151.38	-3.56	302.40	20.00
150.70	-3.43	273.60	20.00
150.70	-3.61	267.60	20.00
151.63	-4.07	309.50	20.00
151.32	-3.89	303.40	20.00
151.38	-3.65	304.10	20.00
145.61	-3.44	272.00	20.00
145.52	-3.35	272.00	20.00
146.28	-3.41	263.90	20.00
146.37	-3.45	267.40	20.00
145.94	-3.31	271.30	20.00
146.38	-3.26	265.70	20.00
154.71	-7.08	48.70	20.00
154.29	-6.76	55.80	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
153.81	-6.65	44.40	20.00
154.87	-6.78	38.00	20.00
154.45	-6.39	27.40	20.00
154.45	-6.52	22.20	20.00
154.28	-6.19	50.10	20.00
154.65	-6.67	36.10	20.00
154.70	-6.73	37.00	20.00
154.94	-6.93	38.50	20.00
154.90	-6.88	36.60	20.00
154.99	-7.06	39.50	20.00
154.75	-6.83	46.00	20.00
154.80	-7.10	29.90	20.00
154.92	-6.71	36.10	20.00
154.92	-7.33	25.10	20.00
154.60	-6.74	35.50	20.00
154.87	-6.77	42.20	20.00
154.91	-7.03	40.80	20.00
154.94	-7.12	38.50	20.00
154.92	-7.12	39.50	20.00
154.76	-6.88	39.60	20.00
154.17	-6.78	36.60	20.00
154.64	-6.85	47.70	20.00
154.89	-7.32	26.60	20.00
154.42	-6.53	41.60	20.00
154.23	-6.84	36.20	20.00
155.00	-7.15	40.80	20.00
153.95	-10.29	183.80	20.00
152.47	-9.83	185.60	20.00
152.45	-9.69	188.40	20.00

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Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
152.37	-9.67	190.20	20.00
147.05	-7.38	84.70	20.00
148.97	-9.68	11.20	20.00
146.10	-6.04	36.90	20.00
146.35	-6.45	25.20	20.00
146.11	-6.04	19.80	20.00
146.08	-6.08	17.30	20.00
146.37	-5.79	16.90	20.00
146.13	-5.97	38.20	20.00
146.16	-6.13	12.20	20.00
145.99	-5.87	32.70	20.00
145.85	-5.83	42.50	20.00
146.74	-6.03	34.00	20.00
146.74	-6.01	33.10	20.00
146.57	-6.49	29.10	20.00
146.21	-6.31	27.10	20.00
149.87	-6.26	0.60	20.00
151.81	-5.56	2.80	20.00
152.16	-5.23	5.60	20.00
149.43	-6.22	11.70	20.00
149.03	-6.79	33.60	20.00
152.70	-5.22	13.10	20.00
149.92	-6.52	10.20	20.00
149.76	-6.35	3.20	20.00
148.83	-6.52	10.30	20.00
147.71	-6.14	7.00	20.00
151.54	-5.53	7.80	20.00
149.26	-6.58	24.70	20.00
149.18	-6.76	18.10	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
148.99	-6.28	23.20	20.00
149.11	-6.37	8.90	20.00
148.85	-6.81	8.60	20.00
153.19	-5.67	27.90	20.00
148.55	-6.23	0.50	20.00
148.01	-6.51	15.00	20.00
147.73	-6.43	6.10	20.00
148.08	-6.25	10.10	20.00
148.77	-6.75	7.70	20.00
151.83	-5.38	3.00	20.00
147.89	-6.46	13.60	20.00
147.90	-6.47	2.90	20.00
148.85	-6.38	0.20	20.00
153.34	-5.54	32.10	20.00
151.25	-5.91	3.50	20.00
148.69	-6.74	0.80	20.00
148.74	-6.73	6.20	20.00
151.21	-6.12	31.40	20.00
151.10	-6.12	0.20	20.00
150.88	-6.30	358.30	20.00
151.77	-5.44	346.80	20.00
151.42	-6.28	351.90	20.00
151.93	-5.49	343.40	20.00
150.38	-6.20	356.80	20.00
150.28	-6.30	350.30	20.00
150.00	-6.34	342.40	20.00
152.03	-5.53	353.80	20.00
152.14	-5.79	354.50	20.00
152.09	-5.51	353.50	20.00

Continued on next page

Table B.5 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
150.61	-6.44	355.80	20.00
150.72	-6.51	353.40	20.00
151.93	-6.01	341.00	20.00
152.58	-5.33	341.60	20.00
148.96	-6.40	341.30	20.00
148.99	-6.56	357.90	20.00
152.18	-5.46	357.30	20.00
151.90	-5.71	352.60	20.00
151.87	-5.58	351.60	20.00
152.07	-5.91	347.10	20.00
152.40	-5.58	344.60	20.00
150.03	-6.27	350.00	20.00
149.10	-6.55	353.80	20.00
149.96	-6.13	349.60	20.00
150.12	-6.19	351.10	20.00
150.25	-5.74	351.10	20.00
152.11	-5.36	344.90	20.00
152.09	-5.40	347.90	20.00
152.11	-5.41	346.00	20.00
151.77	-5.07	347.00	20.00
151.21	-6.03	347.60	20.00
150.36	-6.39	347.60	20.00
150.57	-6.53	342.30	20.00
151.51	-5.66	347.40	20.00
151.58	-5.63	343.20	20.00
152.89	-5.61	344.00	20.00
150.81	-6.14	353.80	20.00
152.12	-5.53	343.50	20.00
150.03	-6.39	359.10	20.00

Datasets 3

The control and input files for the modelling we performed in this study are available at Zenodo via <https://doi.org/10.5281/zenodo.7503511>

Appendix C: Supplementary Materials for Resolving Microplate Kinematics in the Western Banda Arc Using GPS Observations and Multiscale Strain Modeling

Supplementary Materials for
**Resolving Microplate Kinematics in the Western Banda Arc Using GPS
Observations and Multiscale Strain Modeling**

H. Nugroho,¹ M. S. Miller¹, S. McClusky^{1, 2}, B. Hejrani^{1,2}, S. Mousavi¹, R.
Fernandes^{3, 4}, E. Soares,⁵ F. J. G. Jones⁵, and G. P. Almeida⁵

This supplementary document includes 6 supplementary figures (Figure C.1-C.6), and 7 supplementary tables (Table C.1-C.7) for the manuscript titled “Resolving Microplate Kinematics in the Western Banda Arc Using GPS Observations and Multiscale Strain Modeling”

¹Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia.

²Geoscience Australia, Symonston, ACT, 2609, Australia.

³University of Beira Interior, Covilhã, Portugal

⁴Instituto Dom Luís, Covilhã, Portugal

⁵Instituto de Geociências de Timor-Leste (IGTL), Dili, Timor-Leste.

Figure in this document: [C.1](#), [C.2](#), [C.3](#), [C.4](#), [C.5](#), [C.6](#).

Included Table: [C.1](#), [C.2](#), [C.3](#), [C.4](#), [C.5](#), [C.6](#), [C.7](#).

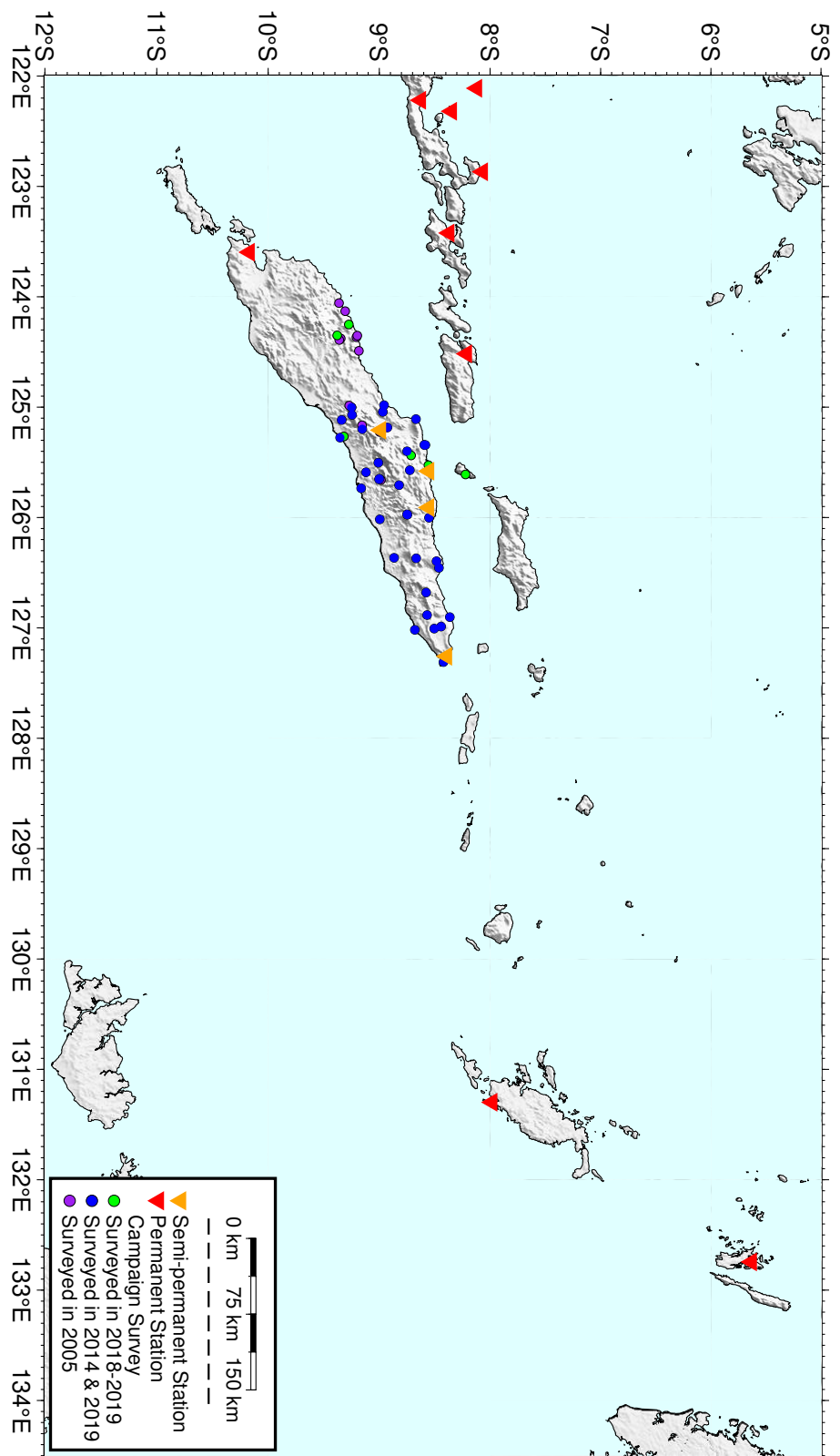


Figure C.1: **GPS** stations in the region, including those used for campaign surveys, semi-permanent installations (in Timor-Leste), and permanent stations (in Indonesia).

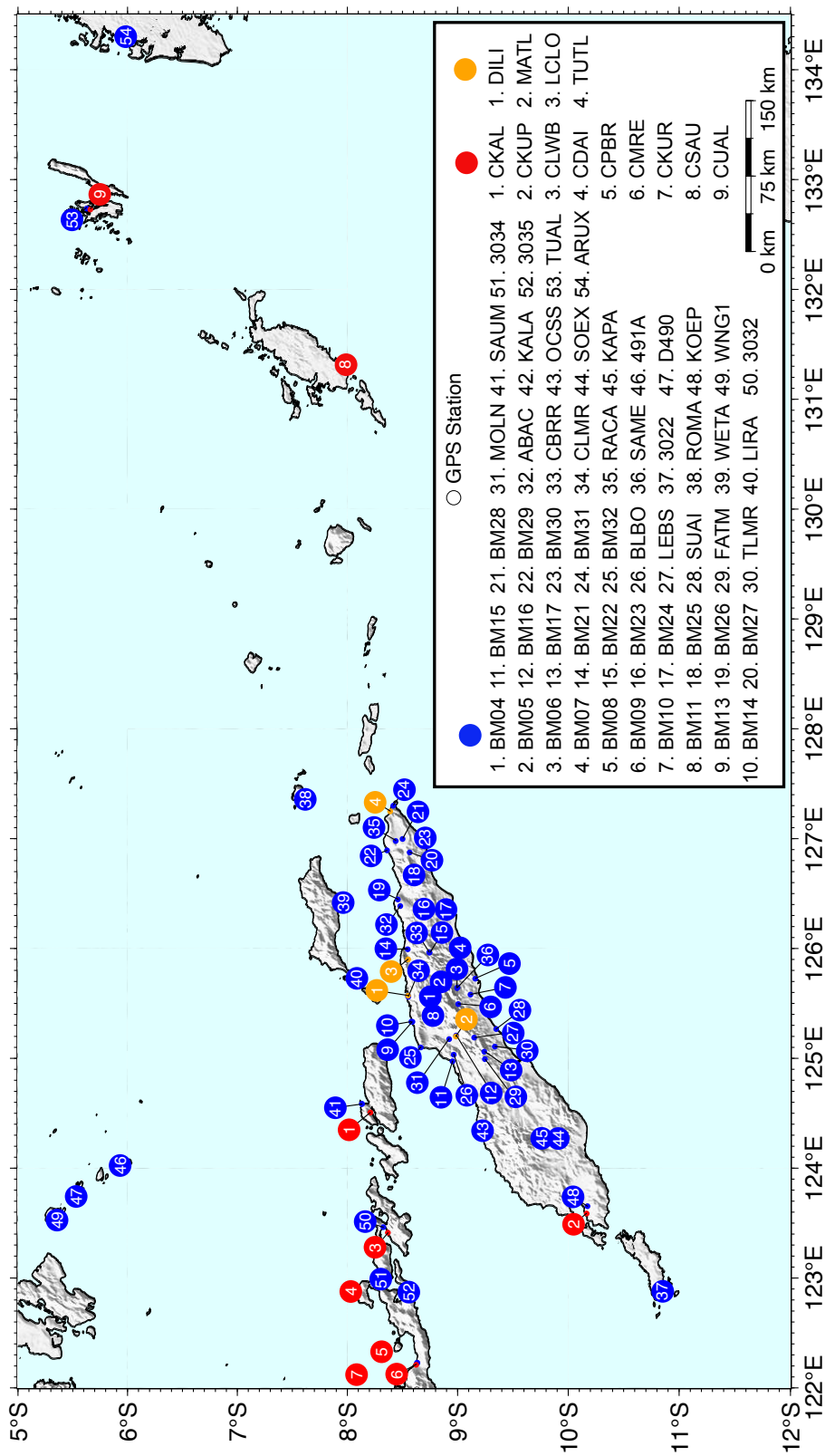


Figure C.2: GPS stations/benchmarks with their codename in the region. Red, orange, and blue indicate permanent, semi-permanent stations, and benchmarks for campaign survey, respectively.

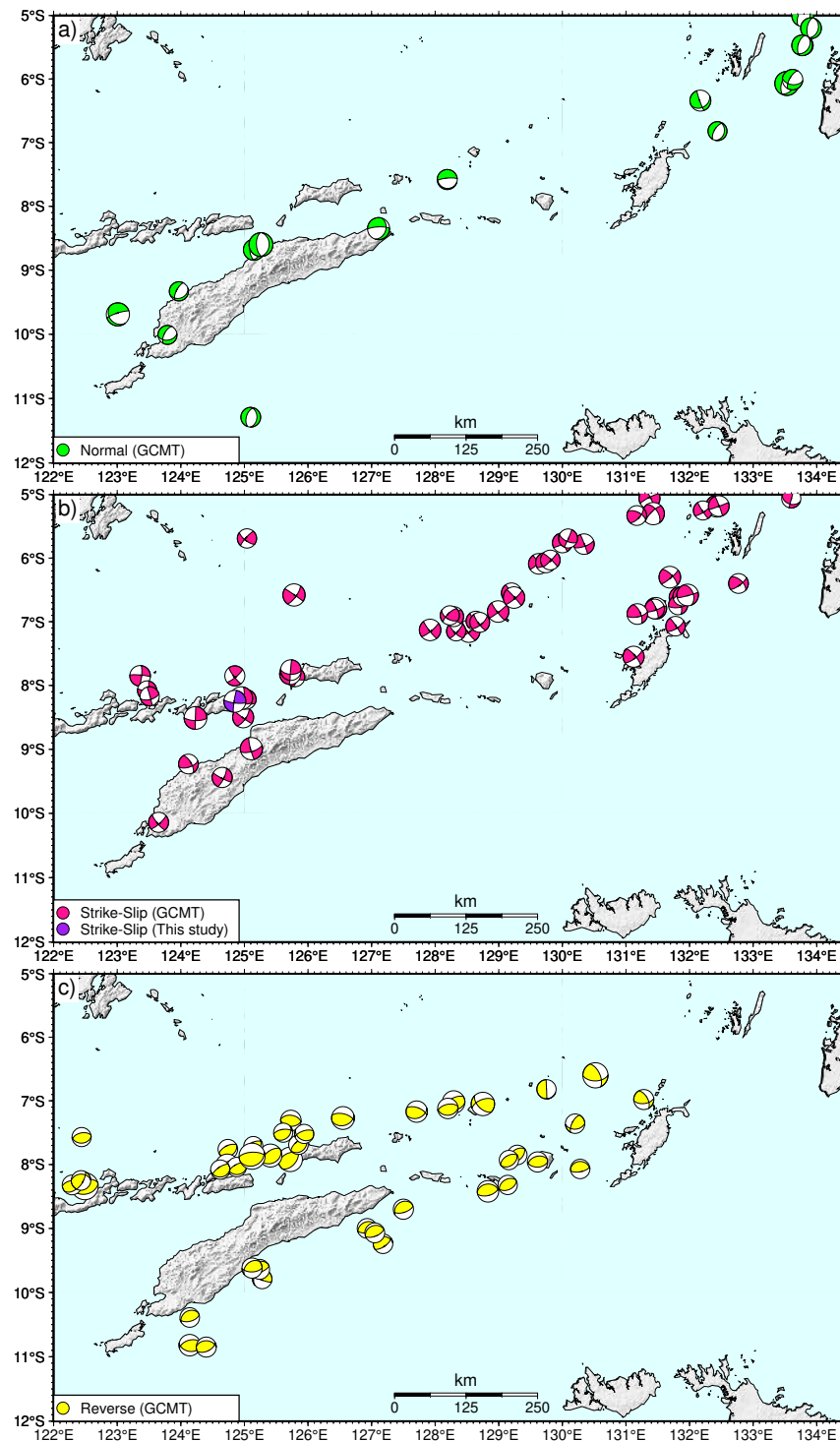


Figure C.3: Earthquake focal mechanisms acquired from Global Centroid Moment Tensor(globalcmt.org) classified into three different groups: a) normal, b) strike-slip, and c) reverse faults using FMC (Álvarez-Gómez, 2019). The purple color in Figure C.6b shows focal mechanism of 2015 Alor earthquake is from Nugroho et al. (2024).

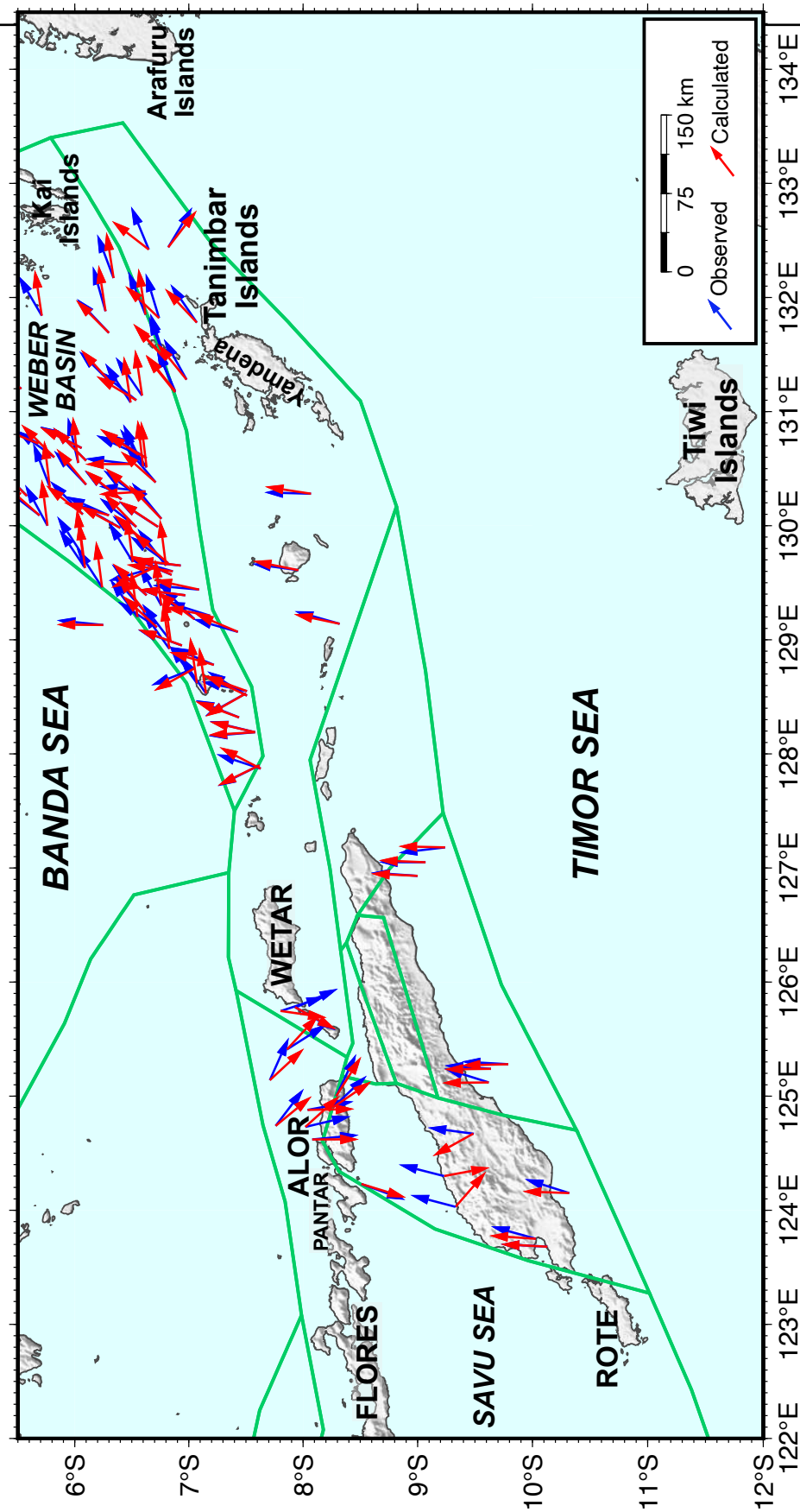


Figure C.4: Observed and calculated fault slip vectors. Observed slip vectors are derived from centroid moment tensor data from the Global Centroid Moment Tensor (GCMT) catalog (Benz, 2017, globalcmt.org), following the method of Aki and Richards (1980). Calculated slip vectors are obtained from the TDEFNODE block model.

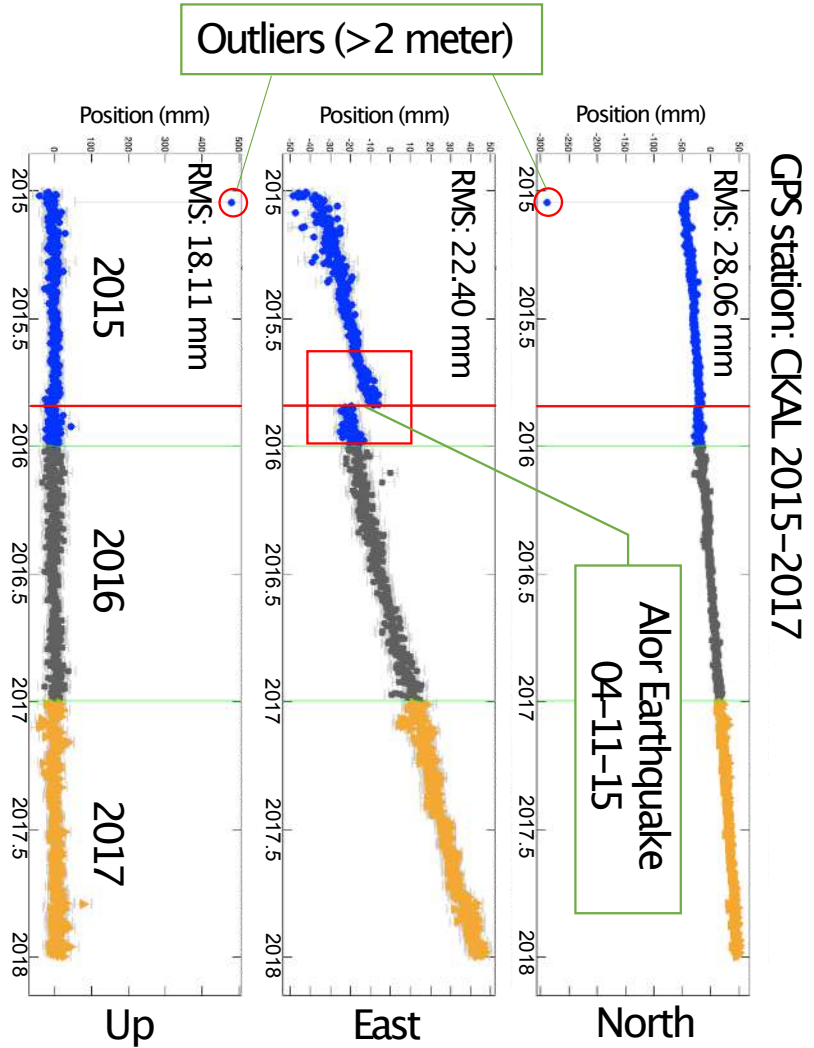


Figure C.5: GPS observation time series from 2015-2017 showing outliers and jumps. The vertical red lines mark the jump due to Alor earthquake which occurred on 4 November 2015. A red square highlights the large offset of horizontal position in south-east direction. The outliers are indicated by blue dots inside red circles possibly due to unknown local disturbance.

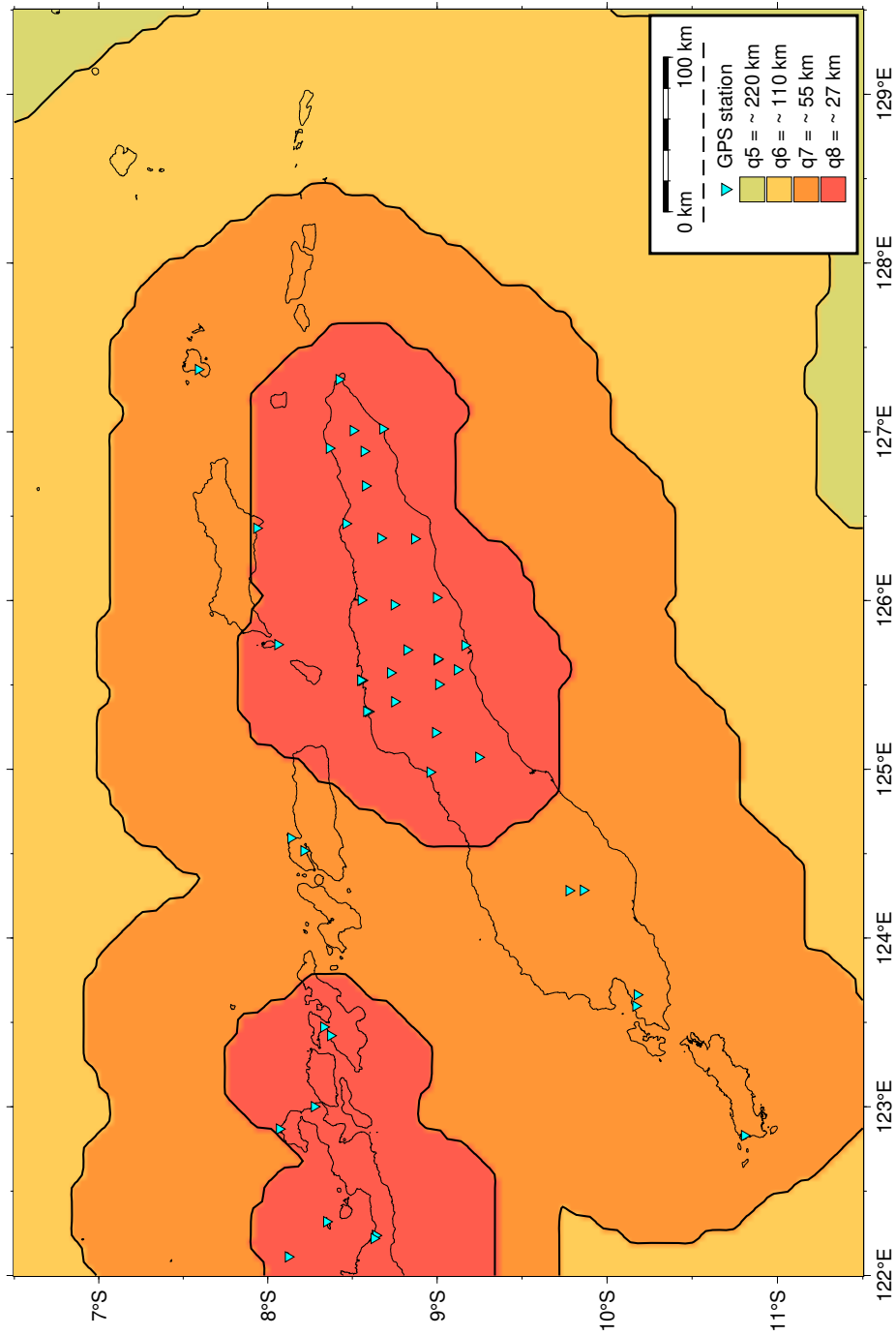


Figure C.6: Selection of spherical wavelets based on the density of [GPS](#) observation in the region. The color shows the maximum q-scale wavelet for each filled area. Where the stations are dense (e.g., $q8$), wavelets with all scales are available (up to $q8$).

Year (DOY).

[illegible]

Table C.2: Timetable of GPS campaign survey conducted at 29 sites in Timor-Leste in 2014, represented by [DOY](#).

[illegible]

Table C.3: Linking of 2005, 2018 and 2019 [GPS](#) campaign survey in Timor-Leste. Light gray shading in the table content indicates a semi-permanent station.

Station	Year	DOY	Year	DOY	Year	DOY	Year	DOY
MOLN	2005	303-305					2019	163
CBRR	2005	265-267					2019	160
CLMR	2005	364-366					2019	165
ABAC	2005	271-274					2019	160
RACA	2005	267-270			2018	156-157	2019	159
SAME	2005	268-271			2018	159-160	2019	162
DILI					2018	156-365	2019	001-172
MATL			2017	137-299				
BLBO	2005	292-295					2019	249
FATM	2005	290-293					2019	251
MLNA	2005	216-217						
OCSS	2005	319-322						
SUAI	2005	297-304					2019	250
TLMR	2005	296-300					2019	252

Table C.4: Linking of 2014 and 2019 GPS campaign survey in Timor-Leste.

Station	Year	DOY	Year	Doy
BM02	2014	256, 265		
BM03	2014	263-264		
BM04	2014	256, 266-268, 283-284	2019	219
BM05	2014	268, 275-276	2019	220
BM06	2014	275-276	2019	222
BM07	2014	273, 275	2019	224
BM08	2014	275-276, 282	2019	223
BM09	2014	276, 282, 284-285	2019	220
BM10	2014	276-282	2019	222
BM11	2014	256, 265, 267-268, 285	2019	218
BM12	2014	265, 268		
BM13	2014	266, 268	2019	218
BM14	2014	256, 265-268	2019	217
BM15	2014	285	2019	249
BM16	2014	283-285	2019	248
BM17	2014	284	2019	251
BM18	2014	282-284		
BM21	2014	240, 265-267, 274	2019	214
BM22	2014	240, 267-268, 273-275	2019	214
BM23	2014	273-274	2019	211
BM24	2014	273-274	2019	210
BM25	2014	271-273	2019	209
BM26	2014	272, 274-275	2019	210
BM27	2014	270, 272	2019	207
BM28	2014	270	2019	207
BM29	2014	270-272	2019	206
BM30	2014	270-272	2019	207
BM31	2014	270	2019	201
BM32	2014	285	2019	227

Table C.5: The [GPS](#) data analyzed in the study, including the coordinates, velocities, and uncertainties are presented with respect to the Australian Plate reference frame. Please refer to Table [C.6](#) & [C.7](#) for details on the [GPS](#) observation epochs. Lon-Longitude; Lat-Latitude; Ve-Velocity in east direction; Vn-Velocity in north direction; σ_e -Uncertainty in east direction; σ_n -Uncertainty in north direction; ρ -velocity NE correlation coefficient. The data derived from the [UNAVCO](#) are the raw [GPS](#) data processed in our study.

Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
159.800	-11.303	-2.45	-3.66	4.200	1.800	0.000	BELL
158.936	-54.499	-0.24	-13.05	0.100	0.100	-0.091	MAC1
152.833	-10.688	-5.13	3.90	2.700	1.500	0.000	MISI
151.867	-10.225	2.59	4.20	0.850	0.480	0.000	STRA
150.873	-10.226	1.60	3.34	1.290	0.950	0.000	HEHE
150.728	-10.302	1.16	0.36	0.800	1.470	0.000	LELE
150.662	-10.613	0.48	1.62	0.450	0.690	0.000	SMRI
150.426	-10.407	1.55	2.04	0.930	0.830	0.000	DAIO
150.337	-10.310	0.82	1.08	0.520	0.990	0.000	ALT2
150.268	-10.683	0.71	1.65	0.950	0.650	0.000	SIBA
149.866	-10.398	1.22	0.68	0.490	0.570	0.000	NUBE
148.980	-35.399	4.88	-3.57	3.620	2.940	-0.010	TIDB
147.056	-19.269	0.11	-0.27	0.300	0.300	0.000	TOW2
144.249	-7.424	-0.32	-1.55	0.560	0.450	0.044	KIKO
144.186	-7.322	0.12	-0.98	1.130	0.950	-0.002	KOPB
143.723	-6.879	-1.11	-0.64	1.180	1.060	0.124	GOB1
141.643	-5.126	-1.88	-0.70	1.120	1.070	-0.001	TELE
140.414	-8.518	1.11	1.08	1.000	0.770	0.000	BUKE

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Table C.5 – continued from previous page

Lon	Lat	V_e mm/yr	V_n mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
140.301	-6.099	5.21	1.00	1.480	1.140	0.000	TNMH
141.278	-6.127	1.21	0.24	0.660	0.580	-0.021	KIUN
141.267	-7.348	0.02	-0.29	0.330	0.290	0.011	AIAM
141.220	-5.258	0.21	0.45	0.670	0.580	-0.008	TABU
141.142	-5.667	0.26	-0.84	1.010	0.550	0.013	NING
137.092	-4.145	6.99	-3.75	2.850	2.510	0.000	TPRA
134.312	-5.987	4.74	3.10	2.500	0.600	0.096	ARUX
133.886	-23.670	0.17	0.20	0.253	0.246	-0.003	ALIC
132.745	-5.632	-17.96	1.95	0.200	0.200	0.000	CUAL
131.298	-7.984	-2.33	-1.84	0.300	0.400	0.000	CSAU
131.133	-12.844	-0.17	0.15	0.305	0.317	0.000	DARW
130.488	-3.104	-44.82	-16.12	1.000	1.000	0.000	CBLA
128.960	-3.300	-31.73	-46.33	0.290	0.220	0.000	MSHI
128.190	-3.060	-42.87	-44.79	0.490	0.360	0.000	PIRU
128.185	-3.696	-28.26	-33.60	0.300	0.300	0.000	CAMB
128.080	-3.710	-29.33	-42.59	0.300	0.260	0.000	AMB1
127.369	-7.590	-0.45	-10.04	0.560	0.530	0.021	ROMA
127.308	-8.420	-0.13	-9.62	0.650	0.490	0.034	BM31
127.017	-8.679	1.21	-11.33	0.700	0.520	0.011	BM30
127.006	-8.504	1.09	-11.54	1.010	0.810	-0.008	BM28
126.988	-8.442	0.16	-7.41	0.100	0.100	0.012	RACA
126.901	-8.363	1.10	-7.81	0.420	0.380	0.013	BM29

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Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
126.884	-8.568	2.26	-14.56	0.500	0.580	0.032	BM27
126.679	-8.577	-2.38	-17.52	0.420	0.370	0.030	BM25
126.455	-8.461	-1.57	-14.69	0.780	0.620	0.003	BM26
126.429	-7.935	0.93	-10.99	0.580	0.520	-0.024	WETA
126.396	-8.484	-0.55	-8.57	0.150	0.130	0.052	ABAC
126.369	-8.667	-1.02	-13.60	0.460	0.740	0.010	BM23
126.365	-8.867	-0.20	-12.10	0.330	0.790	0.005	BM24
126.016	-8.995	-3.16	-10.94	0.810	0.690	-0.006	BM07
126.001	-8.551	-2.53	-13.81	0.670	0.550	0.017	BM21
125.974	-8.746	-4.24	-12.52	0.410	0.350	0.023	BM22
125.971	-8.749	-1.98	-9.12	0.150	0.130	0.026	CBRR
125.739	-8.059	0.89	-12.76	0.500	0.490	-0.003	LIRA
125.707	-8.822	-3.56	-9.47	0.550	0.460	-0.022	BM05
125.653	-9.002	-0.19	-10.54	3.510	2.880	-0.022	SAME
125.589	-9.119	0.58	-12.04	0.800	0.650	0.001	BM10
125.571	-8.724	-1.86	-13.88	1.700	1.190	0.025	BM04
125.569	-8.556	0.03	-11.49	0.210	0.180	0.033	CLMR
125.528	-8.549	-0.60	-13.27	1.510	1.520	0.003	DILI
125.503	-9.009	-3.14	-10.44	0.810	0.660	0.020	BM09
125.399	-8.749	-2.28	-14.92	0.420	0.350	0.021	BM11
125.343	-8.583	-2.07	-13.96	0.520	0.420	0.023	BM14
125.341	-8.594	-2.07	-13.97	1.110	0.900	-0.068	BM13

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Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
125.276	-9.353	-2.11	-12.37	0.410	0.400	0.012	SUAI
125.217	-8.990	-2.50	-8.34	0.420	0.340	0.003	BM16
125.183	-8.927	-3.43	-11.18	0.420	0.410	0.004	MOLN
125.070	-9.244	-2.91	-15.72	0.390	0.040	0.023	BM17
125.003	-9.250	-1.15	-12.72	0.440	0.420	0.003	FATM
124.982	-8.957	-2.08	-14.16	1.250	0.940	-0.001	BM15
124.517	-8.213	-8.54	-28.19	0.620	0.640	-0.002	CKAL
124.476	-9.454	-4.14	-26.05	0.390	0.610	0.005	CKEF
124.280	-9.776	-2.24	-18.15	0.510	0.480	-0.005	KAPA
124.035	-5.905	-11.42	-41.46	1.000	0.920	-0.028	491A
123.753	-5.503	-14.18	-44.17	1.030	0.920	-0.044	D490
123.597	-10.169	-1.28	-23.65	0.500	0.410	-0.002	CKUP
123.539	-5.328	-16.90	-44.33	3.630	3.160	0.014	WNG1
123.473	-8.330	-8.98	-34.39	0.530	0.490	0.005	3032
123.422	-8.371	-9.02	-35.78	0.620	0.570	-0.011	CLWB
123.001	-8.275	-6.20	-38.92	2.480	2.320	0.011	3034
122.868	-8.069	-6.51	-38.18	1.000	0.950	-0.001	CDAI
122.829	-10.807	-5.26	-27.05	0.600	0.550	-0.017	3022
122.599	-5.609	-13.57	-55.06	0.760	0.710	0.034	BBAU
122.545	-3.963	-13.19	-50.91	1.160	1.150	-0.001	CKEN
122.319	-8.348	-10.06	-37.48	0.350	0.350	-0.002	CPBR
122.220	-8.627	-9.16	-32.69	0.390	0.420	-0.010	CMRE

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Table C.5 – continued from previous page

Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
122.075	-5.474	-10.30	-57.82	0.920	0.870	0.026	TLGA
122.110	-8.121	-3.67	-51.86	1.140	1.130	0.000	CKUR
121.988	-10.466	-4.86	-33.77	0.500	0.480	-0.002	3049
121.783	-10.522	-4.90	-33.16	0.500	0.480	-0.001	3050
121.768	-7.406	-7.20	-55.75	1.020	1.000	-0.001	CTOA
121.766	-8.707	-7.14	-36.34	0.570	0.550	-0.021	ENDE
121.489	-4.582	-13.89	-59.98	0.830	0.700	0.008	TOAR
121.078	-7.382	-9.43	-57.40	0.760	0.660	-0.008	CBON
121.019	-8.821	-10.11	-41.49	0.510	0.480	-0.011	3042
120.905	-2.595	-17.86	-58.65	2.040	1.340	0.022	MLLX
120.490	-8.311	-10.67	-45.49	0.530	0.510	-0.004	CREO
120.482	-6.492	-10.41	-62.11	0.890	0.790	-0.022	APTC
120.478	-8.597	-10.76	-41.35	0.570	0.520	-0.011	RUTE
120.301	-9.669	-7.64	-39.93	0.480	0.470	-0.002	WAIN
119.650	-3.978	-14.24	-65.28	0.560	0.520	-0.010	PARN
119.549	-5.060	-11.39	-65.29	0.470	0.450	0.004	UJPD
119.408	-5.135	-11.61	-64.69	0.640	0.370	-0.003	CMAK
119.492	-8.589	-12.19	-48.08	3.720	1.340	0.012	KOMO
119.219	-9.390	-9.43	-43.57	0.300	0.300	0.000	WAIK
118.693	-8.543	-13.65	-54.54	0.940	0.880	-0.001	BIMA
117.641	0.558	-17.65	-68.01	1.050	0.990	-0.005	TNJB
117.415	-8.489	-10.76	-57.44	0.520	0.490	0.001	3066

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Table C.5 – continued from previous page

Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
117.097	-20.981	-0.64	0.19	0.300	0.300	0.005	KARR
116.840	-1.256	-14.29	-66.88	1.680	1.710	-0.002	CBAL
116.815	-1.272	-15.95	-67.41	1.240	0.850	0.037	BLKP
116.360	-8.635	-9.37	-59.10	5.850	5.140	-0.004	3074
116.101	-8.561	-11.80	-60.48	0.680	0.460	-0.007	ANAN
116.076	-8.728	-9.16	-59.43	1.090	1.110	-0.001	CLBR
115.471	-8.543	-12.21	-62.31	0.630	0.560	0.016	CPBI
115.347	-29.047	-0.58	0.22	0.300	0.300	-0.012	YAR2
115.146	-8.818	-11.20	-61.60	0.310	0.300	-0.004	CDNP
115.058	-8.150	-10.22	-66.53	0.420	0.410	-0.006	CSRJ
113.693	-8.175	-13.57	-62.70	1.150	1.140	-0.001	CJEM
114.680	-8.147	-10.60	-64.60	1.080	0.960	0.021	BALI
114.628	-8.393	-11.87	-63.06	0.400	0.350	0.000	CCAK
114.440	-7.838	-11.00	-65.94	1.650	1.580	-0.004	CBRN
114.389	-8.451	-7.20	-62.77	1.830	2.020	0.003	CMCR
114.375	-8.212	-12.15	-63.52	2.290	2.260	0.000	CNYU
114.110	-8.534	-12.42	-62.50	1.860	1.840	0.000	CPES
114.013	-7.703	-12.43	-62.93	0.590	0.580	-0.005	CSIT
113.875	-7.018	-13.27	-66.19	0.560	0.540	0.000	CSMN
113.530	-7.719	-11.79	-59.76	1.250	1.260	-0.012	CPAI
113.252	-7.195	-13.65	-66.15	0.560	0.560	-0.001	CSMP
113.115	-8.214	-12.08	-65.60	1.190	1.440	-0.002	CLUM

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Lon	Lat	Ve mm/yr	Vn mm/yr	σ_e mm/yr	σ_n mm/yr	ρ	Site
112.901	-7.651	-12.62	-61.97	0.550	0.640	-0.001	CPAS
112.714	-7.710	-11.53	-62.58	1.620	1.220	-0.058	SKOR
112.663	-7.980	-12.87	-63.58	0.680	0.570	-0.004	CMLG
112.442	-7.466	-10.47	-64.88	0.840	0.760	-0.004	CMJT
112.327	-7.093	-13.25	-65.55	0.570	0.560	-0.001	CLMG
111.986	-6.872	-15.87	-65.59	0.700	0.570	-0.002	CTBN
111.906	-8.066	-12.55	-63.61	0.600	0.550	0.000	CTUL
111.475	-7.847	-10.69	-62.32	1.260	1.070	-0.032	PONO
111.451	-7.606	-11.80	-62.66	0.570	0.520	0.000	CMAG
111.098	-8.196	-12.93	-63.01	0.640	0.580	-0.001	CPAC
110.926	-7.814	-9.35	-64.69	1.550	1.230	-0.085	WGIR
110.914	-7.096	-15.99	-65.75	0.740	0.670	-0.004	CPWD
110.799	-8.191	-15.01	-62.48	4.950	4.880	-0.003	SADE
110.335	-7.893	-14.08	-63.71	6.310	6.250	-0.002	CBTL
110.295	-7.817	-13.42	-66.67	1.350	1.320	0.002	JOGS
110.217	-7.476	-14.75	-64.64	4.540	4.480	-0.001	CMGL
110.208	-7.635	-11.63	-64.16	0.940	0.720	0.012	BUTU
109.653	-7.670	-15.27	-64.02	0.740	0.670	-0.001	CKBM
105.688	-10.450	-3.38	-2.60	0.420	0.300	0.005	XMIS
96.834	-12.188	0.15	-0.65	0.420	0.430	-0.005	COCO
72.370	-7.270	3.17	-0.48	0.530	0.300	-0.001	DGAR

Table C.6: Earthquake slip vectors calculated from [GCMT](#) data.

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
125.11	-8.99	-46.30	20
125.12	-9.62	17.50	20
125.24	-9.64	4.00	20
125.28	-9.79	3.20	20
126.93	-9.00	4.00	20
127.05	-9.07	0.30	20
127.18	-9.24	-6.70	20
127.50	-8.70	7.60	20
128.19	-7.58	-4.80	20
128.83	-8.42	-5.90	20
129.14	-8.32	15.80	20
129.61	-7.96	7.80	20
124.62	-8.08	174.50	20
124.73	-8.02	166.70	20
124.74	-7.76	127.30	20
124.88	-8.04	169.60	20
125.14	-7.71	114.00	20
125.41	-7.86	147.60	20
127.87	-7.63	18.20	20
127.90	-7.62	-26.50	20
128.19	-7.58	13.60	20
128.32	-7.44	21.70	20
128.51	-7.51	31.50	20
128.53	-7.50	-29.00	20
128.53	-7.15	55.20	20
128.55	-7.51	11.70	20
128.62	-7.07	54.00	20
128.75	-7.05	-21.60	20

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Table C.6 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
128.78	-7.22	22.60	20
128.92	-6.83	54.50	20
128.95	-6.94	19.60	20
128.99	-6.84	52.60	20
129.07	-7.43	15.90	20
129.11	-6.72	33.40	20
129.13	-6.25	5.80	20
129.18	-7.05	44.10	20
129.20	-6.55	53.80	20
129.21	-7.19	17.70	20
129.24	-6.62	48.30	20
129.30	-6.76	61.30	20
129.39	-6.63	41.50	20
129.39	-6.97	7.00	20
129.44	-7.09	5.20	20
129.46	-6.24	57.00	20
129.57	-6.85	22.70	20
129.60	-6.86	16.30	20
129.63	-6.09	56.00	20
129.63	-6.69	-16.10	20
129.65	-6.80	52.40	20
129.65	-6.93	6.20	20
129.67	-6.82	35.30	20
129.68	-6.51	58.60	20
129.74	-6.07	56.70	20
129.83	-6.65	38.80	20
129.98	-6.40	29.80	20
129.99	-6.54	38.10	20
129.99	-6.73	32.90	20

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Table C.6 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
130.00	-5.76	61.40	20
130.06	-6.76	50.70	20
130.09	-5.69	37.50	20
130.09	-6.30	24.00	20
130.10	-6.07	45.50	20
130.23	-6.41	37.80	20
130.24	-6.58	36.80	20
130.26	-5.58	45.90	20
130.30	-6.62	6.30	20
130.34	-5.78	69.10	20
130.36	-6.10	46.40	20
130.38	-6.71	49.80	20
130.41	-5.08	-145.20	20
130.51	-6.63	55.50	20
130.52	-6.60	64.60	20
130.54	-6.50	6.70	20
130.55	-5.40	56.60	20
130.55	-6.03	77.10	20
130.57	-6.10	45.10	20
130.59	-6.63	32.50	20
130.60	-5.82	35.40	20
130.62	-6.56	24.90	20
130.68	-6.06	27.70	20
130.72	-5.68	29.70	20
130.73	-5.41	37.20	20
131.03	-5.41	32.50	20
131.10	-4.84	-174.30	20
131.17	-5.33	26.10	20
131.20	-5.53	35.30	20

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Table C.6 – continued from previous page

Longitude (deg.)	Latitude (deg.)	Azimuth (deg.)	Sigma (deg.)
131.37	-5.18	30.10	20
131.38	-5.37	45.70	20
128.83	-8.42	-3.80	20
130.28	-8.07	1.60	20
131.08	-6.49	56.90	20
131.10	-6.54	38.30	20
131.14	-6.59	55.50	20
131.17	-6.88	66.90	20
131.18	-6.88	66.70	20
131.24	-6.33	44.70	20
131.28	-6.98	60.90	20
131.45	-6.80	68.30	20
131.47	-6.79	71.80	20
131.69	-6.30	46.60	20
131.78	-7.07	55.60	20
131.82	-6.74	73.10	20
131.84	-5.71	59.70	20
131.85	-6.62	68.20	20
131.88	-6.27	74.10	20
132.17	-6.34	69.40	20
132.21	-5.25	56.60	20
132.42	-6.65	67.50	20
132.43	-5.18	71.50	20
132.44	-6.82	121.00	20
132.46	-5.18	68.90	20

Table C.7: Summary table of the slip vectors. Lon. denotes longitude, Lat. denotes latitude. HW represents the hanging wall, while FW denotes the footwall. Vp refers to the velocity parallel to the fault (positive values indicate right-lateral motion). Vp 1σ denotes the 1-sigma uncertainty in velocity parallel to the fault. Vn represents the velocity normal to the fault (positive values indicate divergence). Vn 1σ denotes the 1-sigma uncertainty in velocity normal to the fault.

Lon.	Lat.	HW	FW	Vp	Vp 1σ	Vn	Vn 1σ
124.420	-8.216	SUMB	WTIM	-10.49	0.79	-7.21	0.73
124.047	-8.707	SUMB	WTIM	-12.78	0.58	-1.66	0.61
123.650	-9.541	SUMB	WTIM	-12.97	0.58	-0.05	0.42
123.374	-10.453	SUMB	WTIM	-12.97	0.59	-0.39	0.76
114.132	-8.144	EJAV	SUMB	1.51	0.59	-1.09	0.32
113.810	-9.135	EJAV	SUMB	1.50	0.58	0.86	0.33
113.445	-10.169	EJAV	SUMB	1.46	0.59	2.93	0.43
122.808	-11.161	SUMB	AUST	-17.55	0.23	-32.70	0.28
121.984	-11.479	SUMB	AUST	-15.09	0.22	-36.47	0.27
121.031	-11.591	SUMB	AUST	0.75	0.19	-42.23	0.27
119.918	-11.442	SUMB	AUST	6.19	0.19	-45.08	0.25
118.667	-11.311	SUMB	AUST	-2.02	0.19	-49.11	0.24
117.133	-11.271	SUMB	AUST	-2.28	0.19	-53.53	0.25
115.530	-11.163	SUMB	AUST	2.39	0.20	-58.12	0.26
114.051	-10.945	SUMB	AUST	5.97	0.20	-62.11	0.29
128.070	-9.100	ETIM	AUST	0.34	1.26	-5.41	1.56
126.713	-9.429	STIM	AUST	-4.34	0.27	-12.60	0.31

Lon.	Lat.	HW	FW	Vp	Vp 1 σ	Vn	Vn 1 σ
125.339	-10.001	STIM	AUST	-6.46	0.27	-14.52	0.18
125.591	-7.873	SUMB	WTIM	-11.67	0.51	0.17	1.43
112.413	-10.690	EJAV	AUST	-1.10	0.54	-63.19	0.33
110.414	-10.441	EJAV	AUST	-2.62	0.54	-65.07	0.32
108.260	-10.006	EJAV	AUST	9.14	0.59	-66.50	0.54
124.905	-8.207	SUMB	WTIM	-2.45	1.04	-11.95	0.52
124.832	-9.475	WTIM	STIM	-3.97	0.54	3.04	0.45
124.724	-10.028	WTIM	STIM	-4.05	0.54	2.99	0.52
123.966	-10.655	WTIM	AUST	-10.45	0.64	-19.06	0.54
133.422	-6.128	NETI	AUST	-12.10	1.50	-0.47	0.44
133.276	-6.552	NETI	AUST	-4.91	0.69	-10.80	1.35
132.769	-6.920	NETI	AUST	-4.94	0.69	-10.13	1.23
132.109	-7.488	NETI	AUST	-6.21	0.80	-8.47	0.98
131.410	-8.146	NETI	AUST	-6.00	0.79	-7.62	0.82
130.634	-8.605	NETI	AUST	-2.67	0.57	-8.46	0.82
114.818	-7.637	SUMB	WMAK	10.25	0.36	-18.11	0.49
115.838	-7.799	SUMB	WMAK	11.40	0.37	-16.81	0.43
117.048	-7.927	SUMB	WMAK	8.71	0.36	-17.68	0.42
118.237	-7.927	SUMB	WMAK	7.94	0.35	-17.36	0.42
119.351	-7.862	SUMB	WMAK	6.66	0.35	-17.25	0.44
120.300	-7.819	SUMB	WMAK	8.67	0.35	-15.75	0.48

Lon.	Lat.	HW	FW	Vp	Vp 1 σ	Vn	Vn 1 σ
121.062	-7.942	SUMB	WMAK	13.11	0.36	-11.76	0.51
121.731	-8.142	SUMB	WMAK	12.00	0.36	-12.49	0.56
122.559	-8.136	SUMB	WMAK	5.76	0.39	-15.88	0.60
110.436	-7.144	EJAV	WMAK	6.82	0.41	-29.08	0.77
111.089	-7.224	EJAV	WMAK	8.51	0.43	-27.05	0.69
111.797	-7.324	EJAV	WMAK	8.11	0.42	-25.48	0.64
112.655	-7.416	EJAV	WMAK	7.09	0.41	-23.72	0.61
113.744	-7.520	EJAV	WMAK	7.44	0.42	-20.99	0.64
125.417	-8.467	NTIM	NETI	-3.10	0.57	8.13	0.55
125.850	-8.435	NTIM	NETI	1.33	0.54	7.77	0.80
129.439	-8.893	ETIM	AUST	0.10	1.38	-4.56	3.64
122.659	-7.747	EMAK	WMAK	1.59	0.78	-2.10	0.73
121.911	-7.497	EMAK	WMAK	1.20	0.81	-1.78	0.60
121.303	-7.387	EMAK	WMAK	1.07	0.81	-1.41	0.61
120.704	-6.691	EMAK	WMAK	1.27	0.72	1.24	0.68
120.640	-6.158	EMAK	WMAK	1.21	0.71	1.70	0.66
120.368	-5.248	EMAK	WMAK	1.72	0.72	2.00	0.73
120.020	-4.361	EMAK	WMAK	1.60	0.72	2.81	0.89
119.848	-3.660	EMAK	WMAK	1.01	0.78	3.60	1.00
119.769	-2.684	EMAK	WMAK	0.45	0.86	4.46	1.18
119.936	-2.027	EMAK	WMAK	-3.25	1.38	3.79	0.76

Lon.	Lat.	HW	FW	Vp	Vp 1 σ	Vn	Vn 1 σ
126.885	-8.578	STIM	ETIM	1.10	0.40	7.24	0.44
132.923	-4.853	SERA	AUST	13.16	0.49	24.88	0.43
133.195	-5.424	SERA	AUST	10.06	0.46	25.45	0.32
127.225	-7.425	NETI	BAND	-32.03	2.22	-39.75	0.57
126.104	-7.424	NETI	EMAK	-15.14	0.99	-38.17	1.10
126.566	-7.398	NETI	EMAK	-6.09	0.86	-38.81	1.32
123.611	-7.961	SUMB	EMAK	6.48	0.88	-18.25	0.56
124.421	-7.796	SUMB	EMAK	3.89	0.91	-19.09	0.67
125.182	-7.623	SUMB	EMAK	5.94	0.87	-18.67	0.89
114.818	-7.637	SUMB	WMAK	10.25	0.36	-18.11	0.49
115.838	-7.799	SUMB	WMAK	11.40	0.37	-16.81	0.43
117.048	-7.927	SUMB	WMAK	8.71	0.36	-17.68	0.42
118.237	-7.927	SUMB	WMAK	7.94	0.35	-17.36	0.42
119.351	-7.862	SUMB	WMAK	6.66	0.35	-17.25	0.44
120.300	-7.819	SUMB	WMAK	8.67	0.35	-15.75	0.48
121.062	-7.942	SUMB	WMAK	13.11	0.36	-11.76	0.51
121.731	-8.142	SUMB	WMAK	12.00	0.36	-12.49	0.56
122.559	-8.136	SUMB	WMAK	5.76	0.39	-15.88	0.60
126.667	-8.329	ETIM	NETI	0.13	0.51	1.48	0.65
127.469	-8.198	ETIM	NETI	0.18	0.51	0.12	0.93
129.021	-8.479	ETIM	NETI	0.50	1.08	-2.41	3.08

Lon.	Lat.	HW	FW	Vp	Vp 1 σ	Vn	Vn 1 σ
120.704	-6.691	EMAK	WMAK	1.27	0.72	1.24	0.68
120.640	-6.158	EMAK	WMAK	1.21	0.71	1.70	0.66
120.368	-5.248	EMAK	WMAK	1.72	0.72	2.00	0.73
120.020	-4.361	EMAK	WMAK	1.60	0.72	2.81	0.89
119.848	-3.660	EMAK	WMAK	1.01	0.78	3.60	1.00
125.230	-5.743	EMAK	BAND	-23.85	1.95	-5.39	1.28
125.898	-6.069	EMAK	BAND	-24.48	1.86	-5.32	1.28
126.452	-6.367	EMAK	BAND	-22.64	1.96	-12.45	1.18
126.831	-6.840	EMAK	BAND	-10.43	1.79	-25.36	1.70
124.145	-4.894	EMAK	BAND	-22.17	2.19	-6.32	1.38
123.340	-3.615	EMAK	BAND	-16.61	2.75	-12.61	1.14
127.747	-7.583	NETI	SERA	-21.95	2.05	-13.47	1.79
128.290	-7.648	NETI	SERA	-25.28	0.82	3.63	2.36
128.941	-7.427	NETI	SERA	-22.78	0.53	12.72	2.13
129.636	-7.198	NETI	SERA	-25.85	0.74	6.95	1.75
130.419	-7.084	NETI	SERA	-26.11	0.78	7.96	1.47
131.299	-6.878	NETI	SERA	-24.00	0.65	14.84	1.33
132.110	-6.581	NETI	SERA	-22.78	0.64	18.62	1.30
132.694	-6.297	NETI	SERA	-19.76	0.68	23.25	1.35
133.156	-6.008	NETI	SERA	-18.77	0.70	25.35	1.46
127.878	-2.678	BAND	SERA	-8.74	1.18	33.78	2.74

Lon.	Lat.	HW	FW	Vp	Vp 1 σ	Vn	Vn 1 σ
128.660	-2.938	BAND	SERA	-13.67	0.90	33.79	2.42
129.250	-3.221	BAND	SERA	-17.56	0.78	33.29	2.17
129.760	-3.645	BAND	SERA	-26.90	0.87	27.78	1.90
130.179	-4.171	BAND	SERA	-32.03	1.12	23.21	1.62
130.252	-4.802	BAND	SERA	-39.67	1.85	-3.36	0.61
129.910	-5.559	BAND	SERA	-34.70	1.89	-18.50	0.83
129.420	-6.202	BAND	SERA	-33.99	1.88	-18.25	1.38
128.898	-6.708	BAND	SERA	-28.62	1.84	-24.65	1.93
128.063	-7.136	BAND	SERA	-20.73	1.88	-29.87	2.51
125.589	-8.696	CTIM	NTIM	0.47	0.41	-4.69	0.32
126.156	-8.495	CTIM	NTIM	0.55	0.40	-4.42	1.13
125.816	-8.981	STIM	CTIM	1.37	0.25	7.29	0.25
126.608	-8.641	STIM	CTIM	6.17	0.37	0.87	0.30
125.087	-8.498	WTIM	CTIM	-12.33	0.60	0.76	0.88
124.981	-8.868	WTIM	CTIM	-12.34	0.57	-0.68	0.71

Appendix D: GPS Time Series

The appendix [D](#) comprises residuals time series figures derived from processing [GPS](#) campaign survey data spanning the years 2005 (Figure [D.1](#), [D.2](#), [D.3](#)), 2014 (Figure [D.4](#), [D.5](#), [D.6](#), [D.7](#), [D.8](#), [D.9](#)), 2018 (Figure [D.10](#)), and 2019 (Figure [D.11](#)), obtained from locations across Timor-Leste.

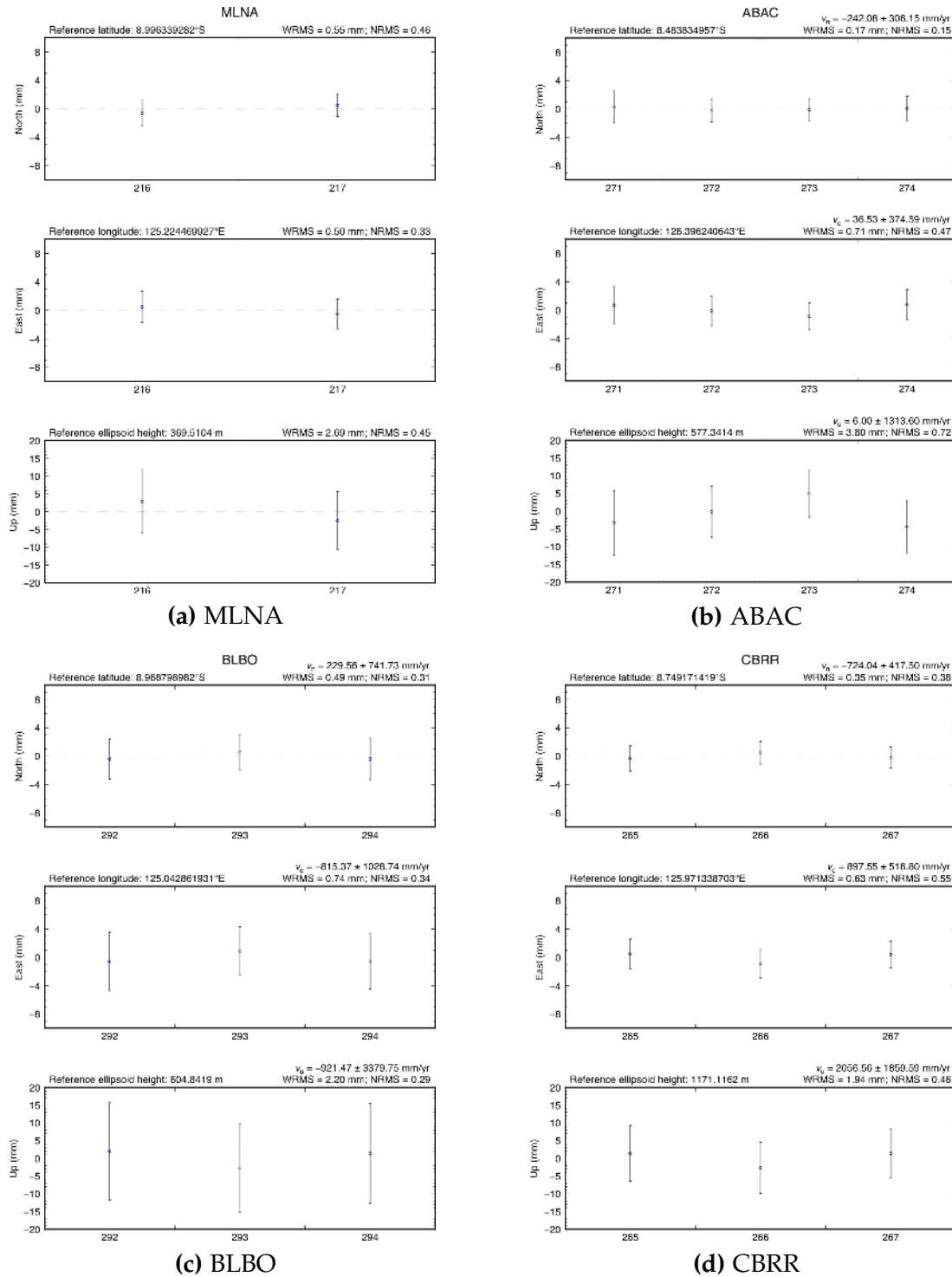


Figure D.1: GPS Time Series from 2005 campaign survey for site MLNA, ABAC, BLBO, and CBRR. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

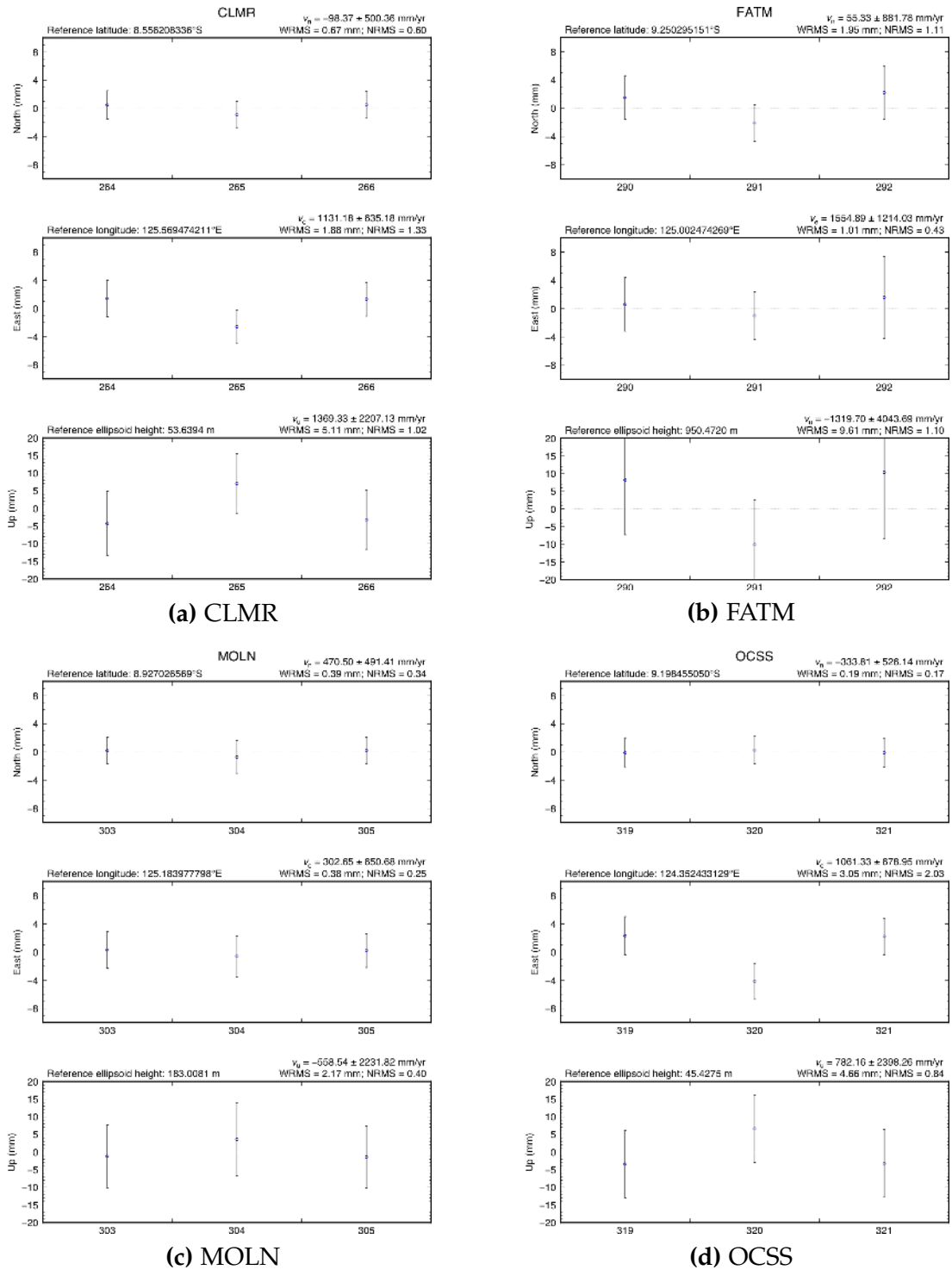


Figure D.2: GPS Time Series from 2005 campaign survey for site CLMR, FATM, MOLN, and OCSS. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

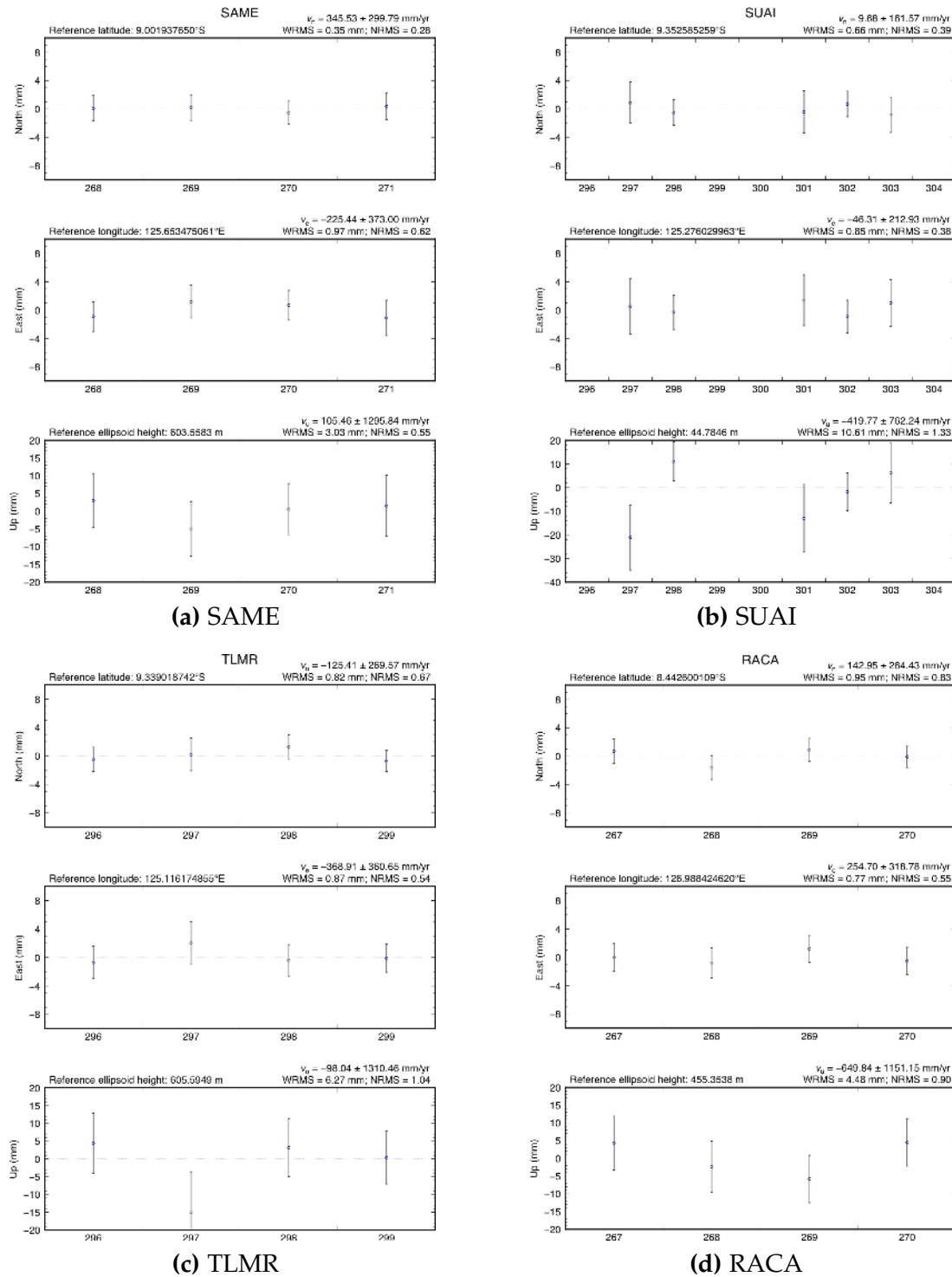


Figure D.3: GPS Time Series from 2005 campaign survey for site SAME, SUAI, TLMR, and RACA. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

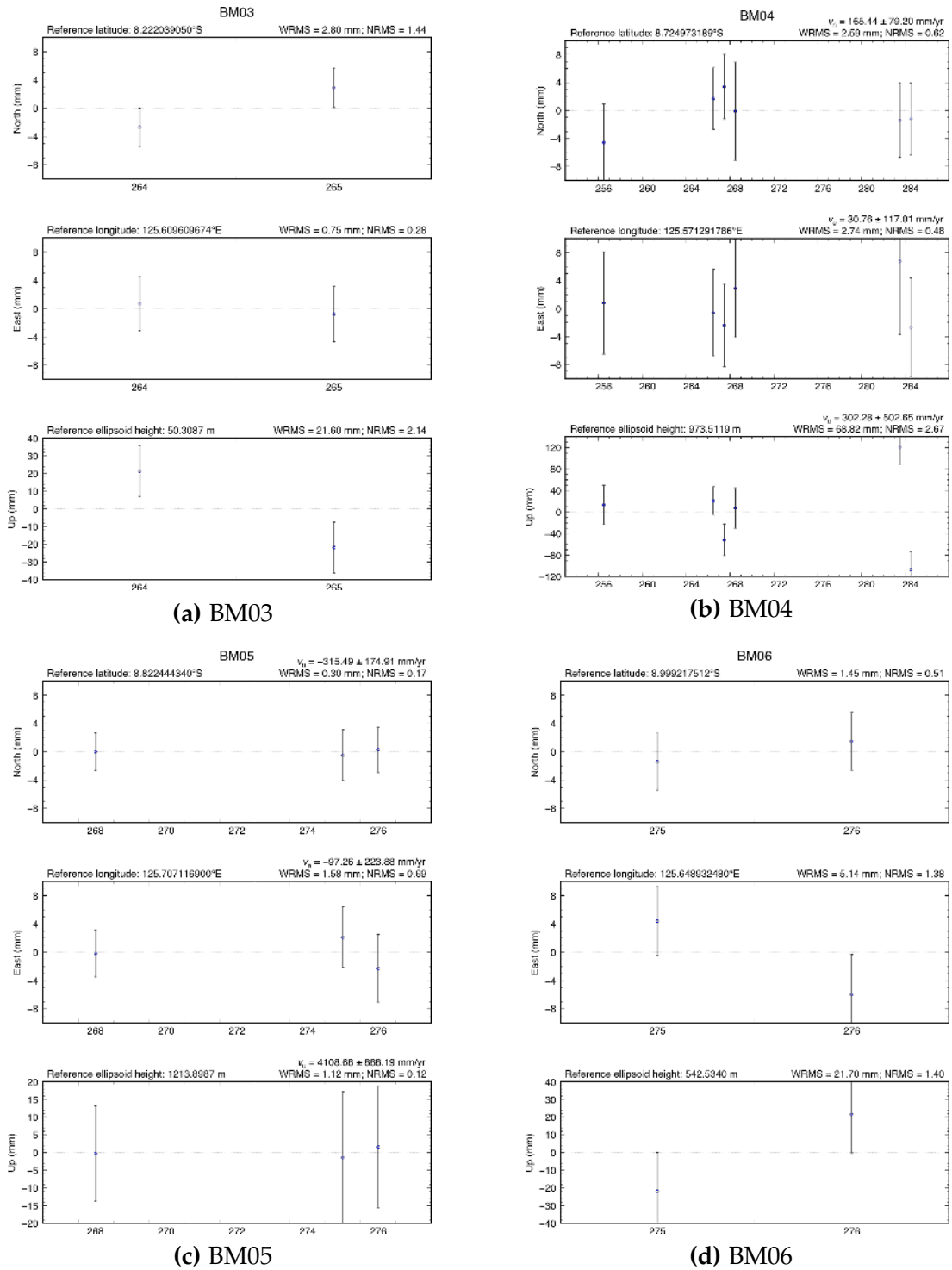


Figure D.4: GPS Time Series from 2014 campaign survey for site BM03, BM04, BM05, and BM06. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

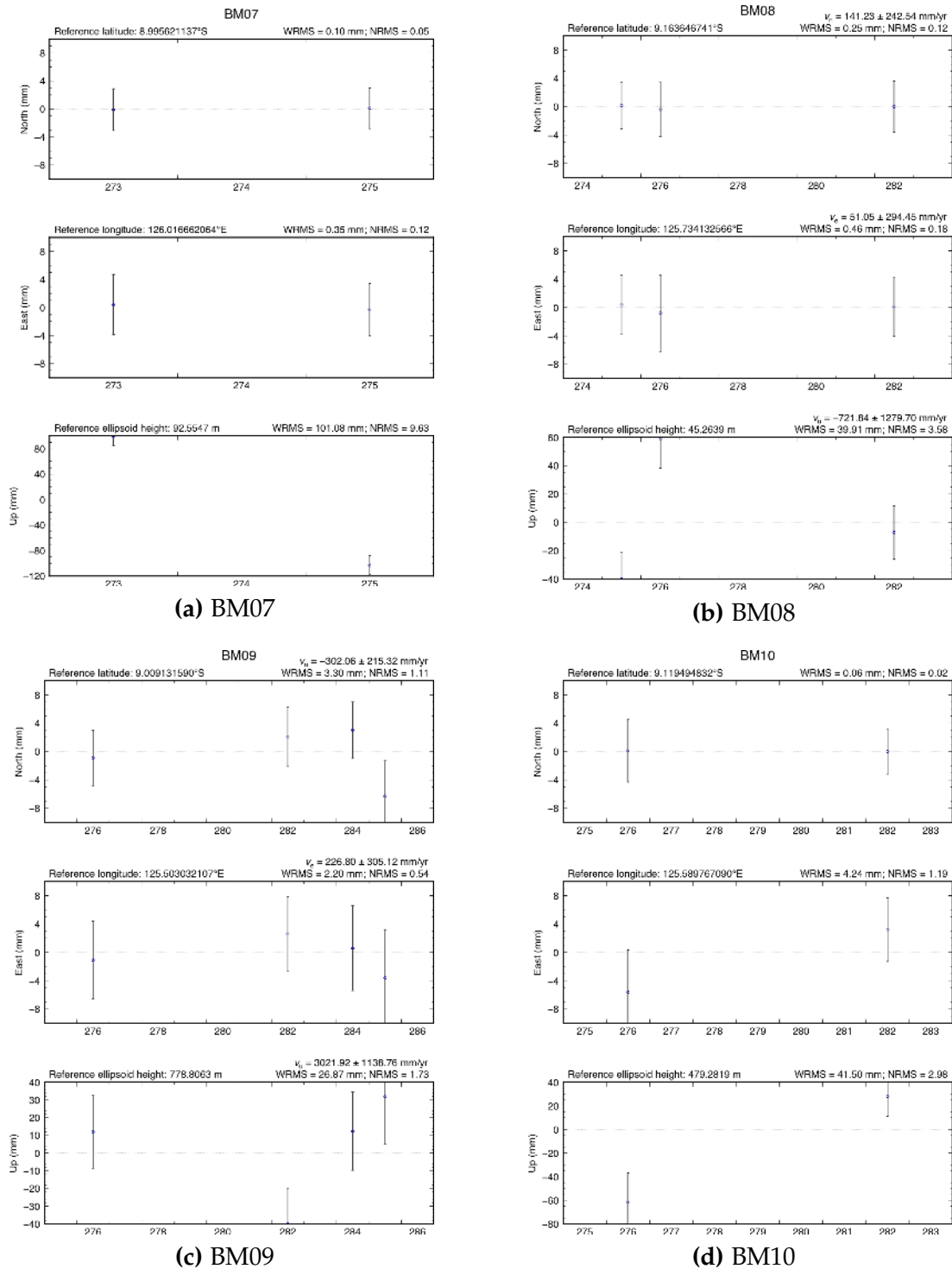


Figure D.5: GPS Time Series from 2014 campaign survey for site BM07, BM08, BM09, and BM10. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

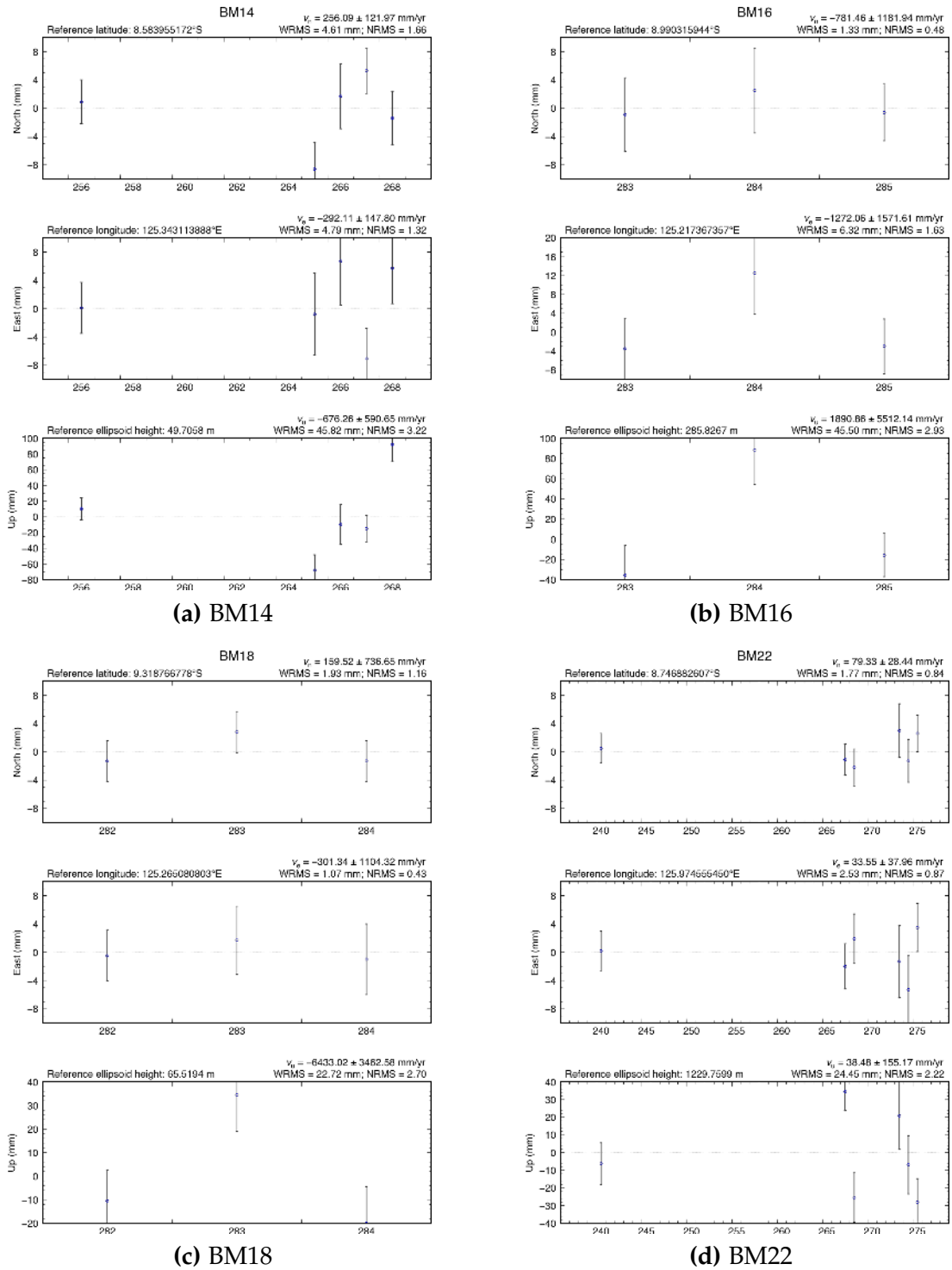


Figure D.6: GPS Time Series from 2014 campaign survey for site BM14, BM16, BM18, and BM22. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

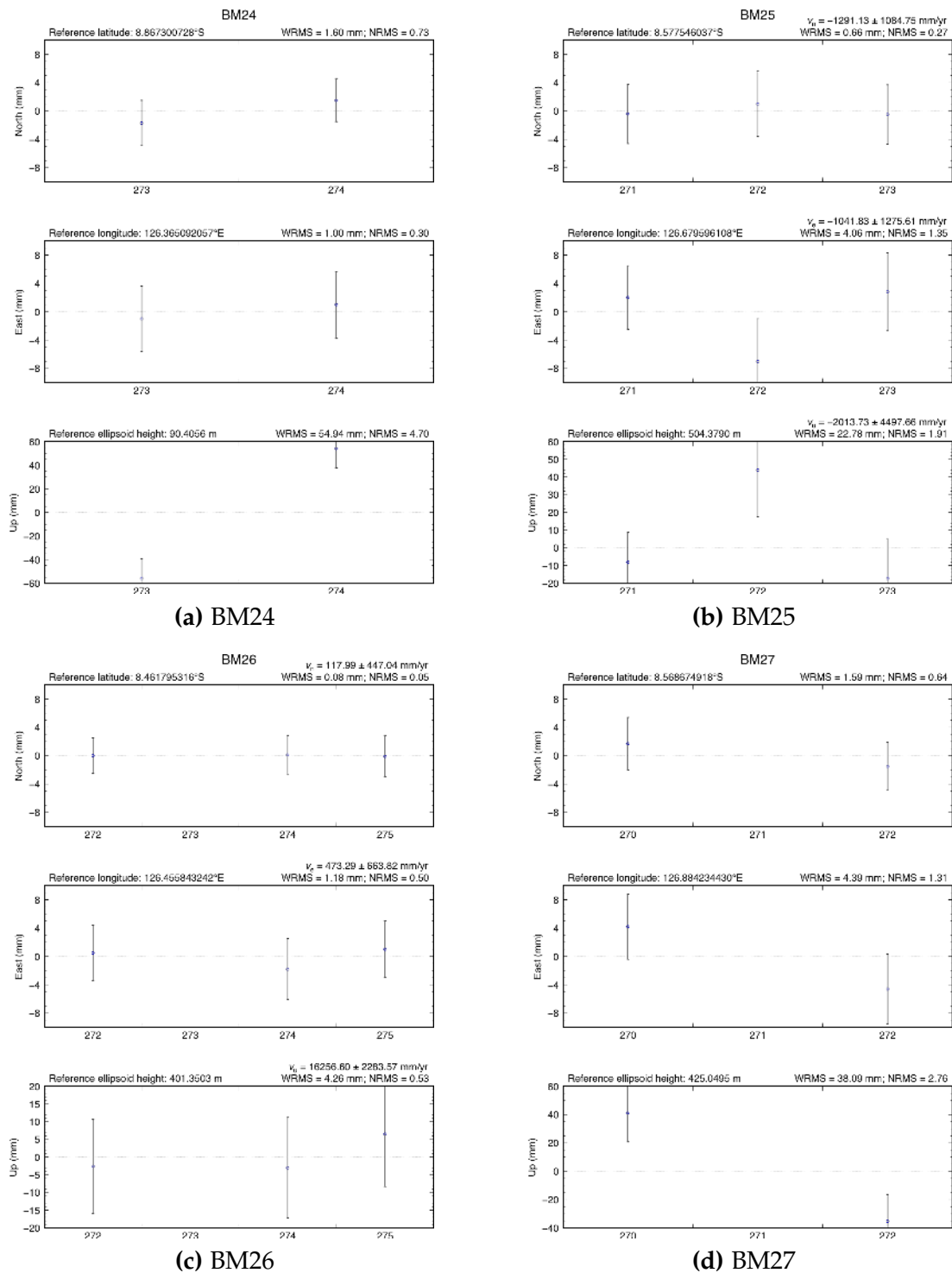


Figure D.7: GPS Time Series from 2014 campaign survey for site BM24, BM25, BM26, and BM27. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

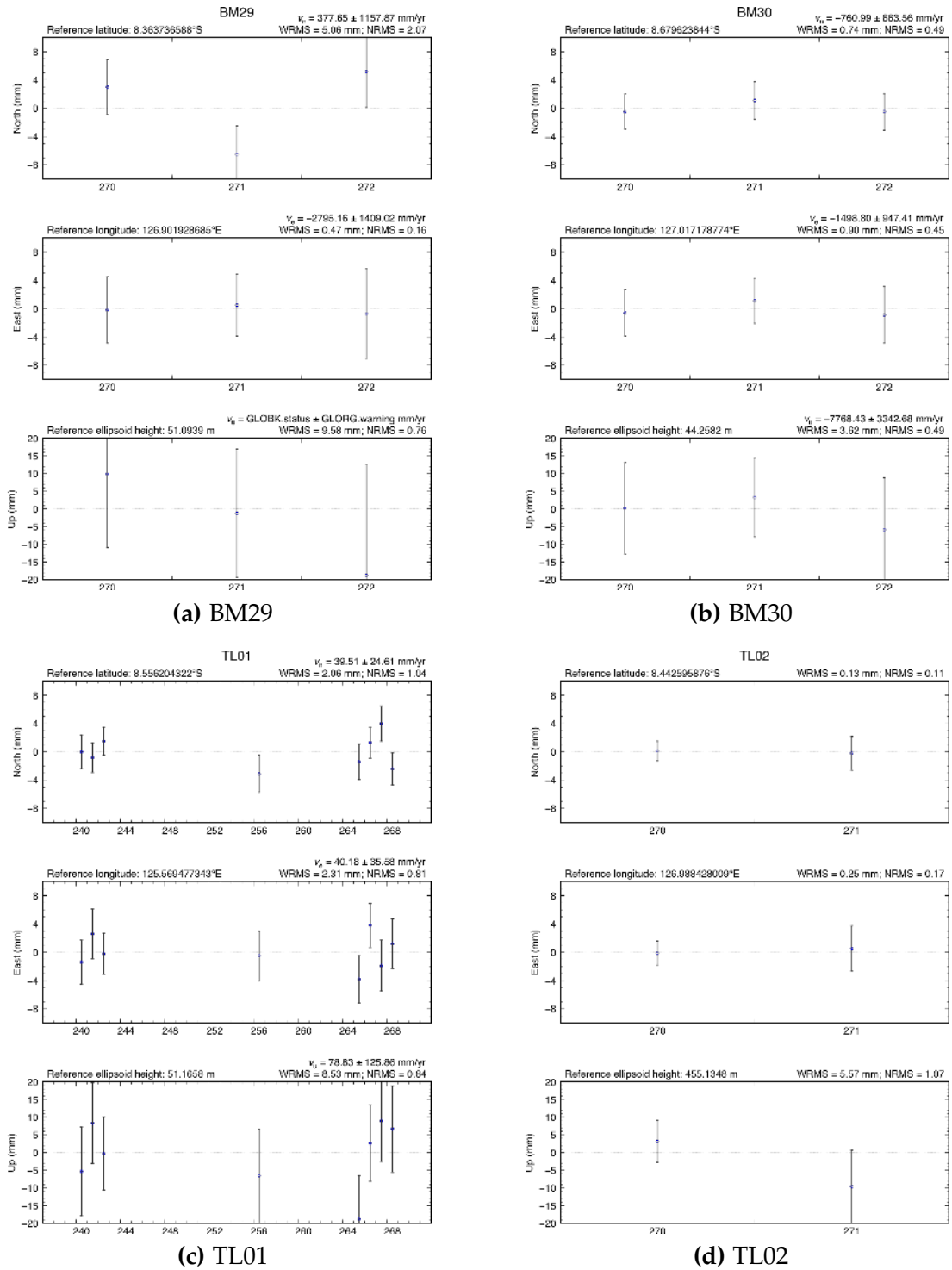


Figure D.8: GPS Time Series from 2014 campaign survey for site BM29, BM30, TL01, and TL02. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

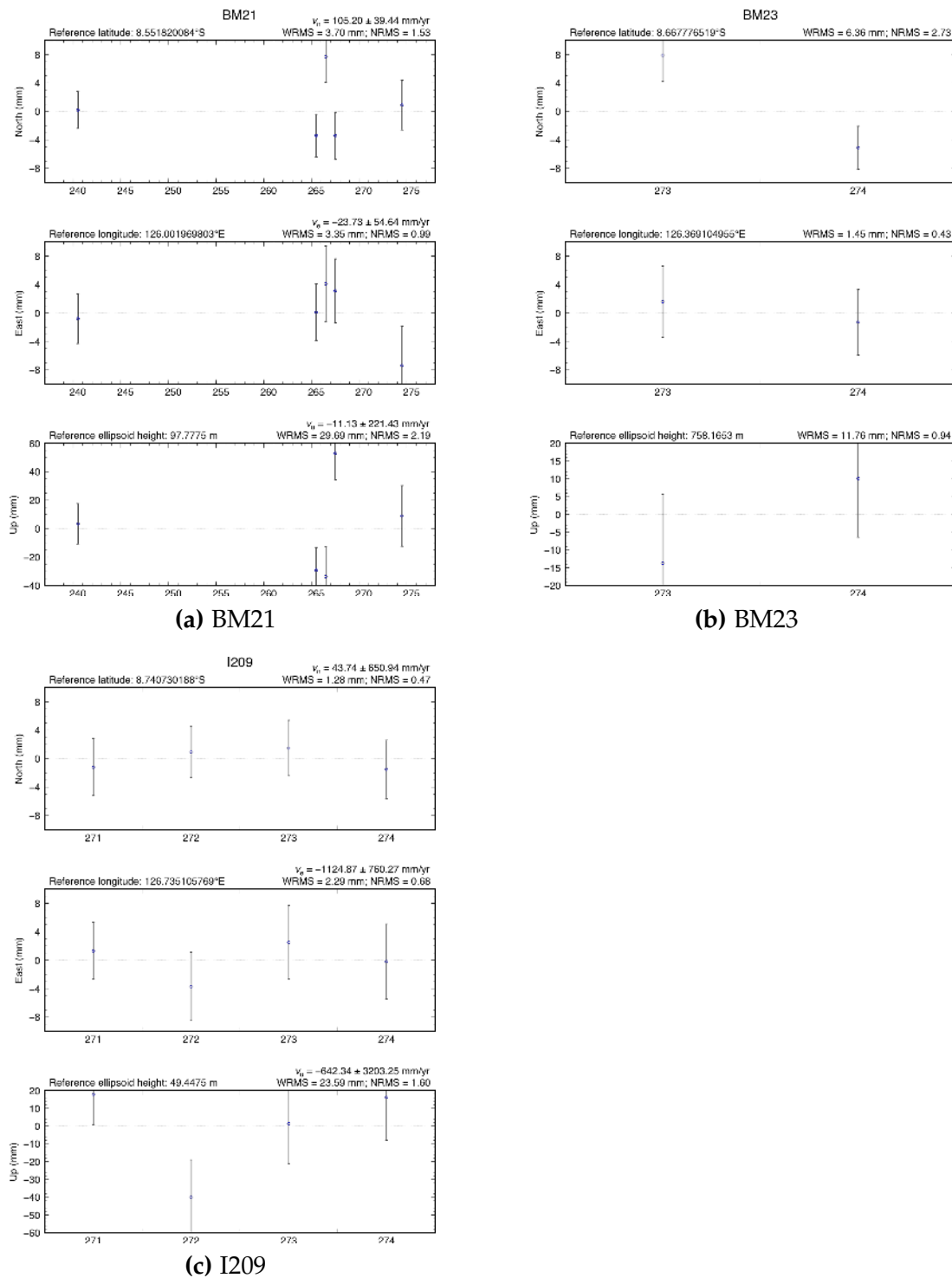


Figure D.9: GPS Time Series from 2014 campaign survey for site BM21, BM23, and I209. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

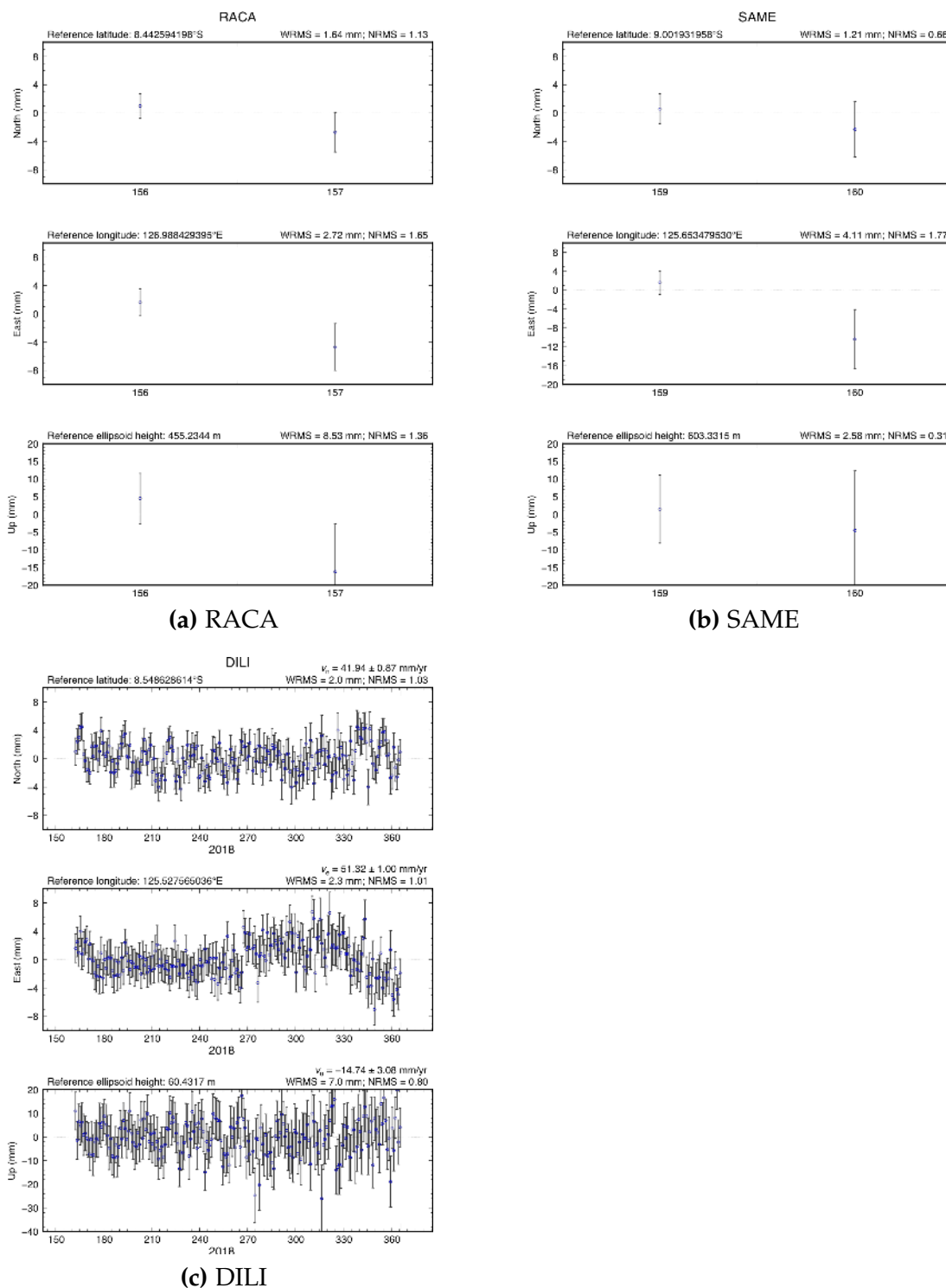


Figure D.10: GPS Time Series from 2018 campaign survey for site RACA, SAME, and DILI. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.

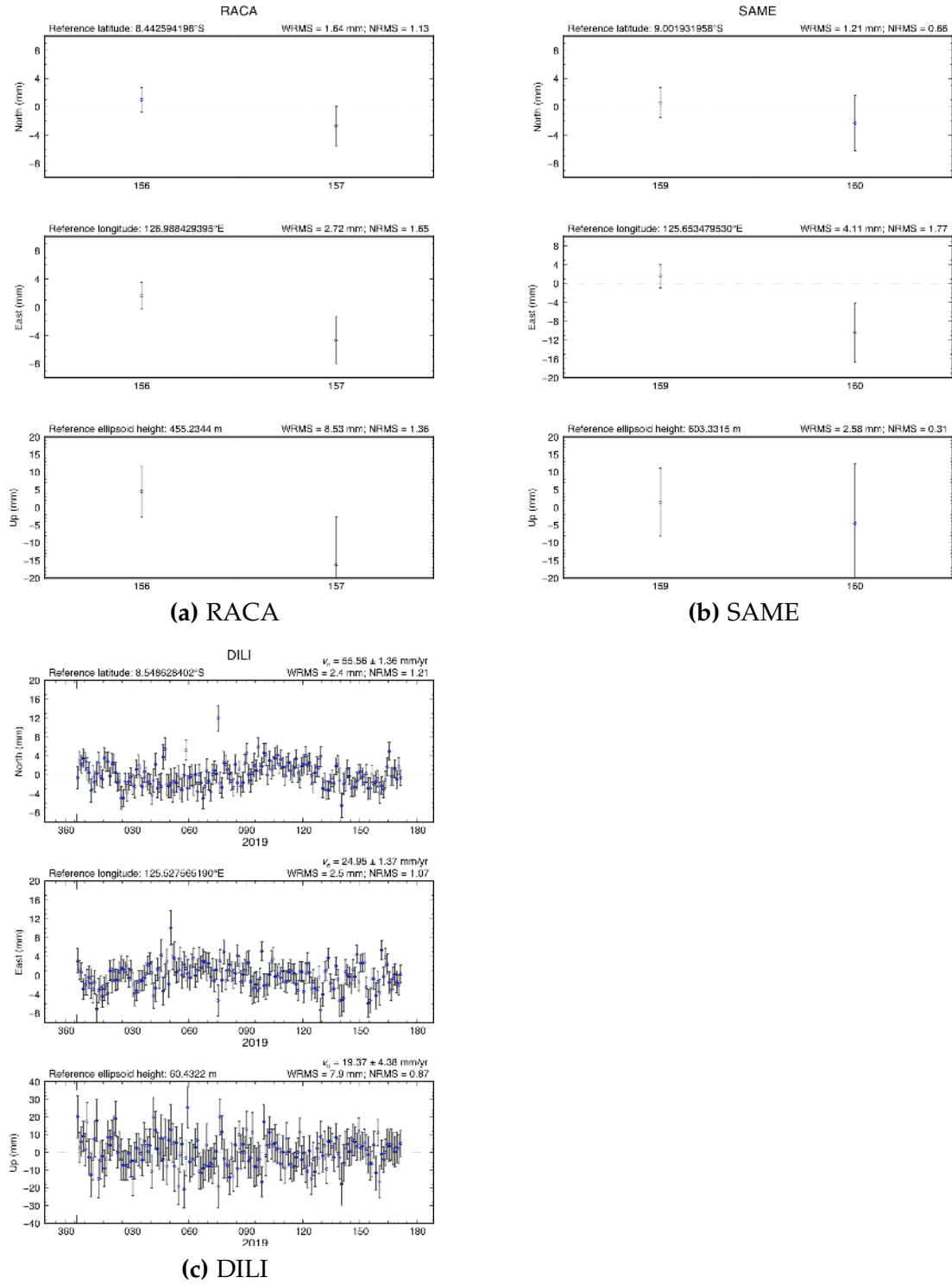


Figure D.11: GPS Time Series from 2019 campaign survey for site RACA, SAME, and DILI. This figure shows the daily position data. The X-axis represents time in Julian days, and the Y-axis shows the position changes in millimeters.