Study of Identification of the Sunda Plate Boundary in Java Island Based on Continuous GPS Observation Data for 2016-2019

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* ABSTRACT.

The Sunda Plate is a minor tectonic plate that stretches on the equator in the eastern hemisphere where the majority of Southeast Asia is located. This particular region of Southeast Asia is considered to be one of the most seismically and tectonically active regions on earth, particularly on the Java Island. Java Island has a very complex deformation and almost all of its areas are not stable areas. The deformation complex of Java Island with many active faults in the region has raised questions about the true southern boundary of the Sunda Plate on Java Island. The geodynamic model used in this research is to identify the boundary, namely the block model. This model is represented by Euler's rotation parameters consisting of Euler's poles (latitude and longitude of Euler's poles) and angular rotational speed from continuous GPS observation data. To identify the boundaries of the Sunda plate on the Java Island, this study used residue vector analysis with a residue value of less than 3 mm / year. In addition, seismity data and geological structure of Java Island are used to identify the *boundaries of the Sunda Plate. The results obtained in this study include the Cimandiri Fault, the Baribis-Kendeng Fault (Subang, Demak, Purwodadi, Cepu, and Waru Segments), Ciremai Faults and Ungaran Faults. Thus, the block rotation model from the plate boundary identification results can be used to properly eliminate the effect of block / plate rotation on the island of Java in order to obtain good elastic deformation information.*

* INTRODUCTION

The Sunda Plate is a minor tectonic plate that stretches across the equator in the eastern hemisphere, where most Southeast Asia is located. The Sunda Plate covers most Southeast Asia, the South China Sea, the Malay Peninsula, most of Sumatra, Java, Kalimantan, and the surrounding shallow seas (Rangin et al., 1999). This particular region of Southeast Asia is considered to be one of the most seismically and tectonically active on earth, particularly on the island of Java. As a result of this plate activity, Java Island experiences slow movement with speeds ranging from 4 s.d. 7 cm/year to the Southeast (Hamilton, 1979). Java Island is located at the meeting point between the Sunda Plate and the Indo-Australian Plate, where on the front line of the meeting, there is a Java subduction zone located in the south of Java Island (Kuncoro et al., 2018).

Previous research has shown that active faults on land dominate the island of Java. Koulali et al. (2016) estimated the shear rate in the Baribis Fault and Kendeng Fault to be 2.3 - 5.6 mm / year and expressed as active faults. Marliyani et al. (2016) also identified part of the active fault zone of Cimandiri, which consists of 6 segments. Java

Island has a very complex deformation, and almost all of its areas are unstable areas (Kuncoro, 2018). The complex deformation of Java Island with many active faults in the region raises the question of where the Sunda Plate's actual southern boundary is on Java Island. Therefore, this study intends to identify the real boundaries of the Sunda Plate in Java Island.

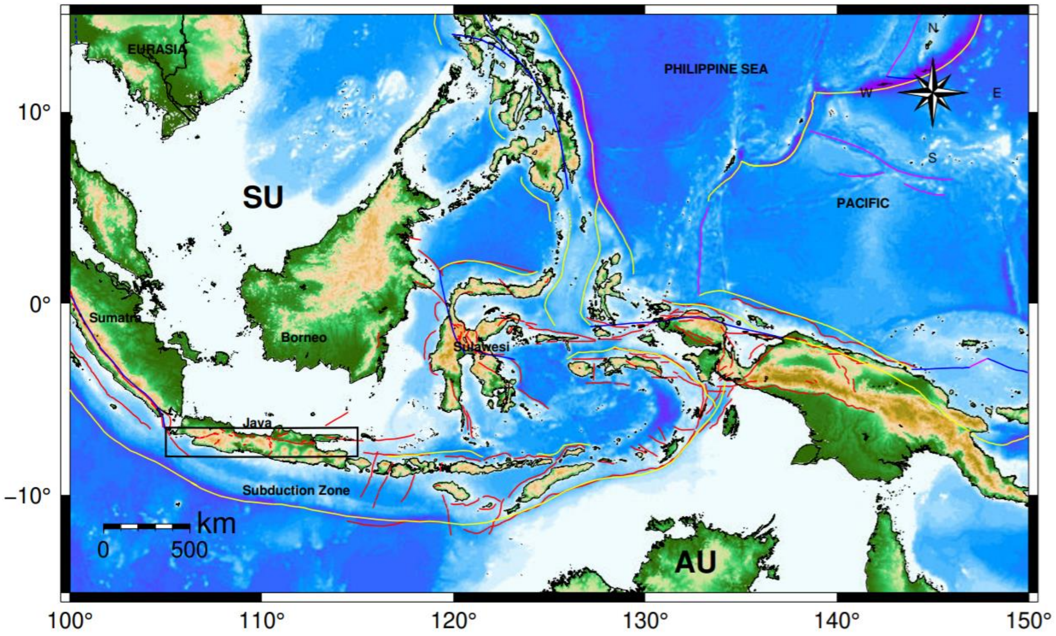

Figure.1 Simple map showing the location of the Sunda Plate and Java, showing the main plate boundaries (in yellow) and the primary faults in the Java region (in red)

The block model was used in this study to determine the boundaries of the Sundanese plate in Java. In this model, the plate/block is assumed to be an object that is rigid and homogeneous so that its movement behavior can be quantified (Thatcher, 2009). This block's movement is represented by Euler's rotation parameters consisting of Euler's poles (latitude and longitude of Euler poles) and angular rotation velocity inverted from continuous GPS observation data (Kuncoro, 2013). In this study, continuous GPS data, seismic data, and the geological structure of Java Island are used to identify the Sunda plate's actual boundaries. Thus, the block rotation model from the plate boundary identification results can be used to properly eliminate the effect of block/plate rotation on the island of Java to obtain good elastic deformation information. In the future study, from the elastic deformation information, a locked area can be estimated in the block/plate boundary zone, and the earthquake magnitude that will occur in the future can be calculated.

* DATA

GPS observations used in this study were obtained from the continuous network of Geospatial Information Agency (BIG), The continuous network includes 48 stations. The continuous started collecting data from 2016 until 2019 and was mainly concentrated in Java (Table 1).

Table.1 Data used to identify the boundaries of the Sundanese plate on the Java

Number	Data	Station	Information	Source
1.	CORS Data Borneo	CNAU, CRAU, CBAL, CBJM, CPKY, CGMS, CPUT, CBAS, CPON, CKTP	2016 – 2019	BIG
2.	CORS Data Belitung Island	CBLT	2016-2019	BIG
3.	CORS Data Natuna Big Island	CNAT	2016-2019	BIG
4.	CORS Data Java Island	CGON, CPSR, CRKS, CTGR, CJKT, CBTU, CLDO, CPWK, CTGL, CPKL, CSEM, CPBL, CMGL, CJPR, CNLR, CTBN, CLMG, CSBY, CSMP, CSMN, CNGA, CMAG, CSUM, CROL, CCIR, CPWD, CMJT, CPAS, CPAI, CSIT	2016– 2019	BIG

* METHOD

In the implementation of this research, there are several stages of research, including:

- Collecting data such as CORS data, IGS data, precision ephemeris, broadcast ephemeris
- Data processing using GAMIT / GLOBK 10.7 software to generate daily solutions and standard deviation
- Calculate the velocity vectors and their standard deviation using MATLAB software
- Estimate the angular rotation vector and Eulerian rotation parameter of the Sunda plate

These activities are to identify the boundaries of the Sundanese plate in Java using geodetic methods.

Stage 1

We process GPS observation data and IGS data as reference points using GAMIT / GLOBK 10.7 software to generate daily solutions and standard deviation. The results were evaluated based on the main criteria to determine whether the processing produced acceptable results, such as all expected data are entered, the data fit the model at the desired level, and the uncertainty is minimal (Herring et al., 2018). Furthermore, making time series and detecting outliers. Previously, a combined file directory was created from GAMIT processing every year of observation so that that processing could be efficiently. The GAMIT h-file contains two solutions, one with ambiguity estimated as actual numbers ("bias-free") and one with resolved ambiguity ("corrected bias"); the htoglb command creates two binary h-files, with an area of glr (GAMIT lose free) and glx (GAMIT lose fixed) then HTOGLB creates two binary h-files in .glr format for free webs and .glx for bound nets. Making an initial time series needs to be done to evaluate statistical data and determine outliers that will impact speed solutions. Then after seeing the outliers, outliers are removed using the tsview program in the MATLAB application. The criteria for outlier removal were carried out using 3σ. The primary purpose of the tsview is to assess the quality of the time series generated by the GLRED process and create a control file for GLOBK, which will remove lousy station positions and account for outliers in the time series.

Stage 2

The calculation of velocity in this study uses TSVIEW. The velocity vector can be estimated using the least-squares method, where the velocity vector is the line gradient of the time series of changes in position (time series). The GNSS velocity vector is then used to estimate the Euler pole parameter. Also, the standard deviation of the velocity vector is calculated using the "Realistic Sigma" algorithm in TSVIEW. The RealSigma calculation used here assumes that the noise process is a first-order Gauss Markov (FOGMEX) process. With this model, the residual correlation time for each coordinate component is estimated by calculating the χ^2/f increase over the successively longer mean residual time. For the white noise error model, χ^2/f will not depend on the average time. With temporal correlation in time series, χ^2/f increases as the residuals are averaged over successively longer time intervals. The residual average character can be seen in the tsview using the "Average" button (Herring, T. A, 2003). The box's value below the button indicates the length of time in days that will be averaged. The statistics of the mean residue are shown in bold on the screen (Figure 2).

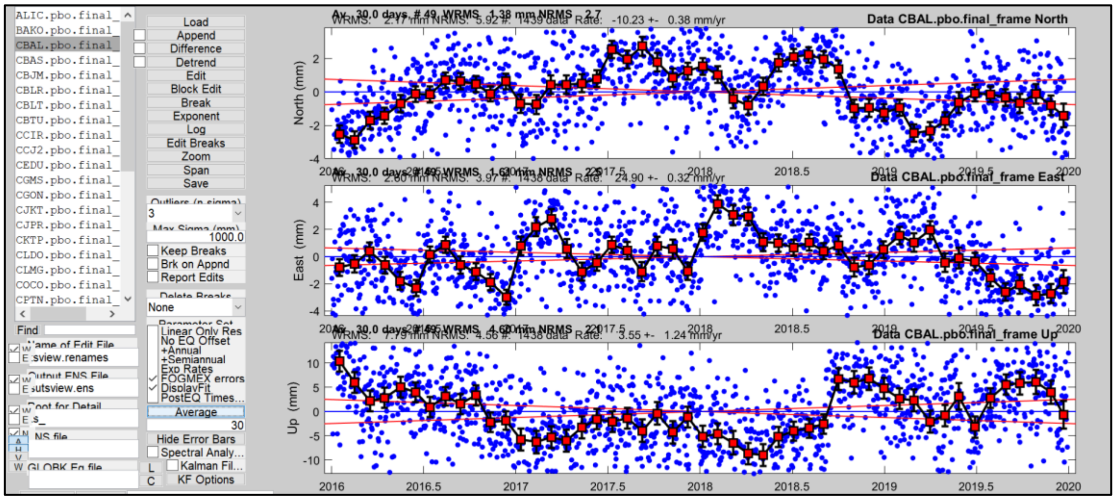

Figure 2. Result of Reaslitic Sigma, the red line shows the 68% probability limit of velocity based on applying the algorithm. The rate in the image is the velocity vector of the station along with its standard deviation in the n,e,u component

Stage 3

Estimating the Euler pole's parameters using a set of mathematical algorithms based on a tectonic plate motion model on a spherical surface estimates the parameters of the Euler pole with the observed velocity from a group of stations located on the same tectonic plate. The software used is the Euler Pole Calculator (EPC Matlab Tools). The chi-square test was then performed to evaluate the Euler parameter estimation results; the chi-square test (χ^2) evaluates the residue between the vector of the observed movement velocity and the velocity vector model movement. In this study, the chi-square test was carried out using MATLAB software.

* RESULTS.

1. GPS Velocity Vectors

The results of the GPS station velocity vectors used to determine the Sunda plate boundary are shown in Figure 3. This velocity vector is obtained from continuous GPS data processing. Based on Figure 3, the majority of the velocity vectors move towards the Southeast with the error ellipse value for each velocity vector is less than 1 mm. This shows that the velocity vector is quite feasible in determining the boundaries of the Sunda plate in Java Island.

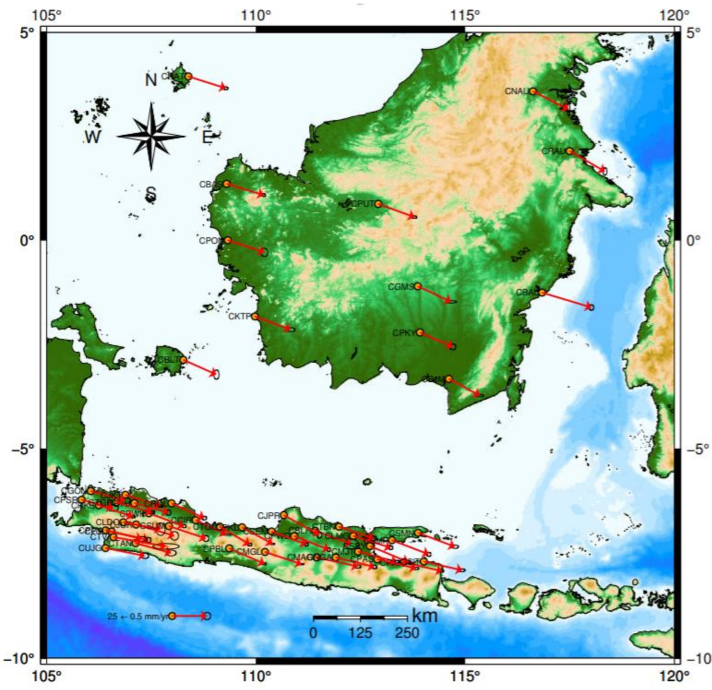

Figure 3. 48 stations of the velocity vector in Figure 2. is shown by a blue arrow with a scale of 25 mm and an error ellipse of 0.5 mm/year.

2. Estimation Results of Euler's Rotation Parameters

This research presents Euler's rotation parameters' estimation results using 25 stations located in Kalimantan and Java Island. Of the 48 stations, only 25 stations are used to estimate Euler's rotation. The results are well determined using the estimating (minimizing residue) iteration. This study estimates that Euler's rotation's best value is 55.773610º (N) ± 4.654020º and 106.032020º (W). ± 6.810010º (Euler's pole), and 0.281700 ± 0.016460 º / million year (angular velocity). The plotting of the residual velocity vectors is shown in Figure 4, and the 25 station velocity vectors that produce the best Euler rotation parameters are shown in Table 2.

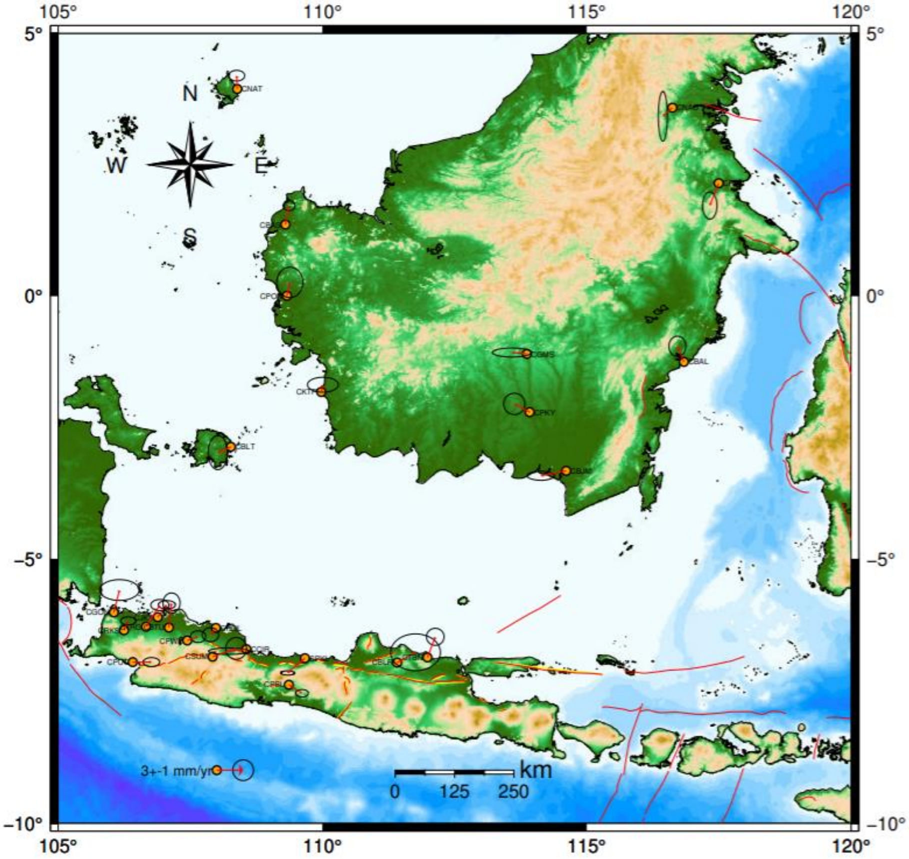

Figure 4. Plotting of the 25 station residual velocity vectors

Table 2. 25 stations are used to estimate Euler's rotation

Station	**Longitude (º)**	**Latitude (º)**	**Residue (mm/tahun)**		**Sigma (mm)**	
			East	**North**	**East**	**North**
CBAL	116,8397	-1,2561	-0,7379	1,7700	0,32	0,38
CBAS	109,3010	1,3607	0,4180	2,1504	0,22	0,19
CBJM	114,6106	-3,3303	-2,8762	-0,5618	0,51	0,17
CGMS	113,8682	-1,1030	-1,7022	0,1538	0,73	0,17
CKTP	109,9776	-1,8288	0,1909	0,8196	0,58	0,28
CNAU	116,6205	3,5860	-1,0781	-0,9694	0,17	0,93
CPKY	113,9204	-2,2134	-1,7359	0,9361	0,40	0,40
CPON	109,3290	0,0036	0,3315	1,5274	0,49	0,57
CRAU	117,4970	2,1493	-1,0089	-2,5324	0,27	0,51
CNAT	108,3877	3,9411	-0,0562	1,5197	0,30	0,20
CBLT	108,2679	-2,8728	-1,4746	-0,6606	0,36	0,64
CPWK	107,4431	-6,5511	1,2302	0,4385	0,29	0,22
CCIR	108,5609	-6,7161	-1,9915	-0,2262	0,76	0,12
CJKT	106,8845	-6,1101	1,0357	1,4046	0,32	0,16
CRKS	106,2463	-6,3579	0,4832	1,0691	0,29	0,15
CROL	107,9846	-6,3125	-0,6129	-0,7728	0,31	0,26
CGON	106,0522	-6,0207	0,6429	2,5486	0,74	0,39
CPKL	109,6694	-6,8870	-1,9729	-1,6772	0,26	0,08
CPUT	106,4114	-6,9608	2,1274	0,0020	0,31	0,17
CBTU	107,0964	-6,3083	0,2924	2,7893	0,32	0,38
CBLR	111,4148	-6,9692	2,0830	1,1642	0,93	0,69
CTBN	111,9864	-6,8722	0,8913	2,3433	0,33	0,32
CTRG	106,6638	-6,2908	1,5650	2,4575	0,34	0,21
CSUM	107,9220	-6,8589	2,6752	0,9411	0,39	0,41
CPBL	109,3642	-7,3885	1,4966	-0,9636	0,24	0,14

The pure block's rotational movement is estimated based on Euler's rotation parameters, and this rotation movement is represented by the velocity of the model movement, whose estimation process is called forward calculation (Kuncoro, 2013). The result of suitability between the model velocity vector and the observation velocity vector in Figure 5. From these figures, the majority of the model velocity vectors are consistent with the observed velocity vectors. That matter proves that the velocity vector of the model is well represented.

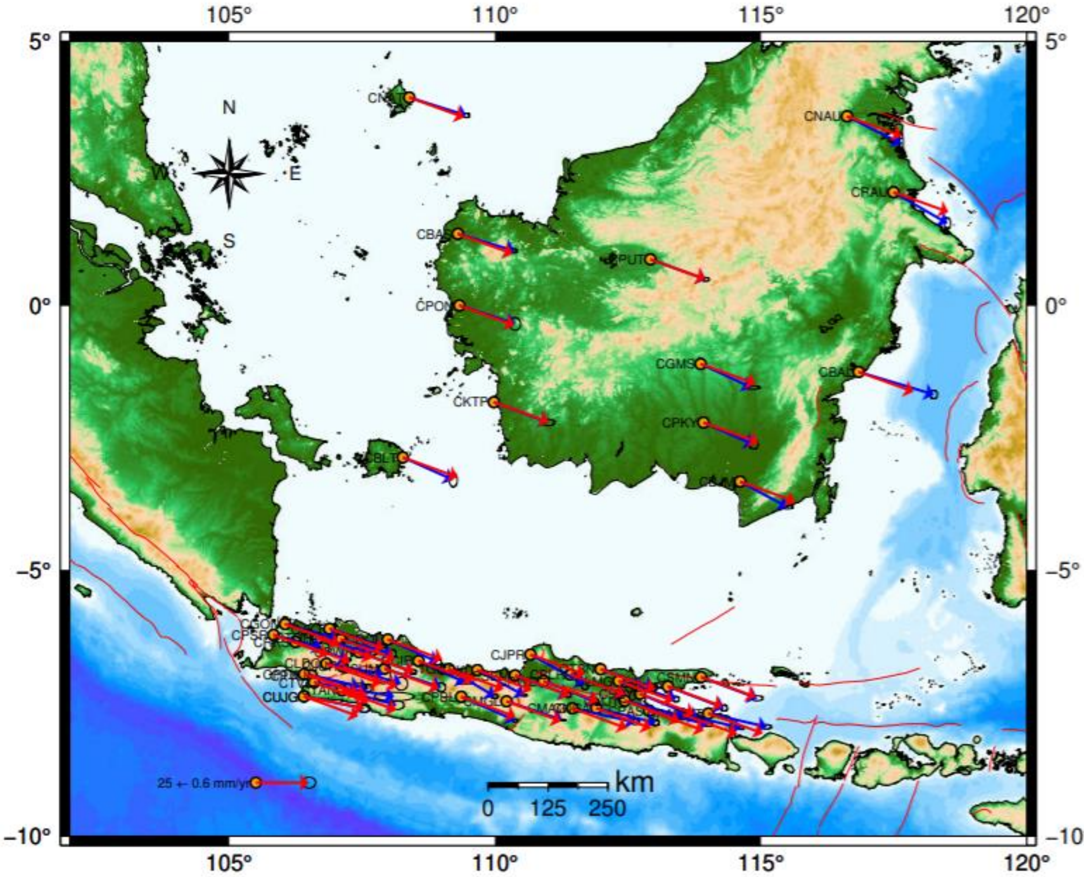

Figure 5. shows the model velocity vector (red) and its error ellipse with an ellipse scale the error is 0.6 mm, and the observed velocity vector (blue) along with the error ellipse with an elliptical scale the same.

To test the correctness of the results Euler’s parameter in this study, it is necessary to make a comparison with the results of the other Sundanese plate Euler rotation parameters from previous studies, plotting the results of the comparison of Euler's rotation parameters with other studies is shown in Figure 6.

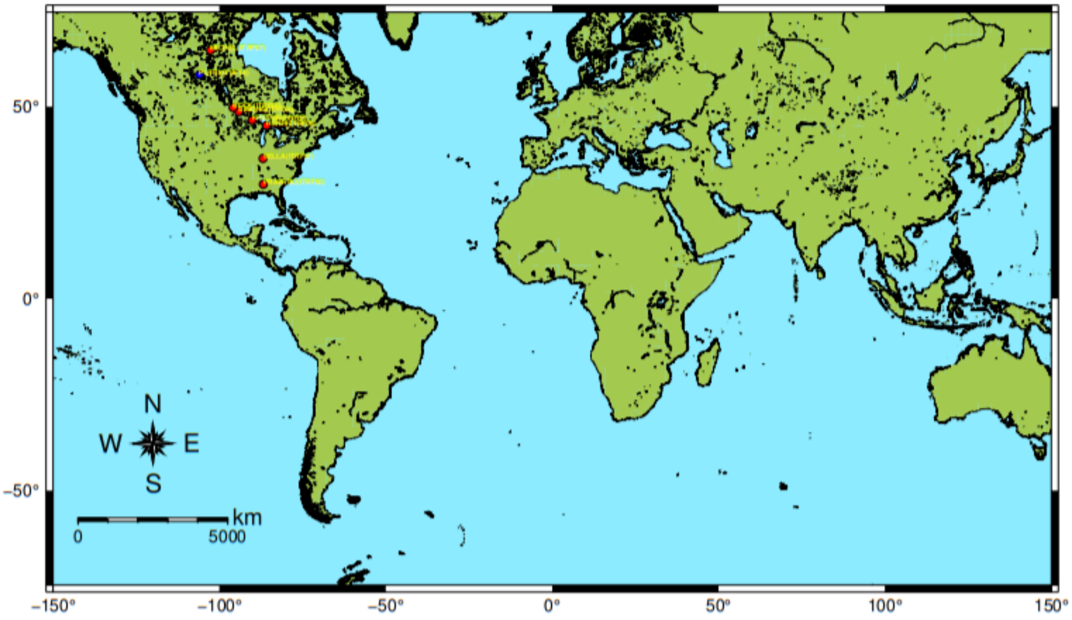

Figure 6. Plotting of Euler's Rotation Parameters with Other Research

3. Illustration of the Sunda Plate Boundary in Java Island

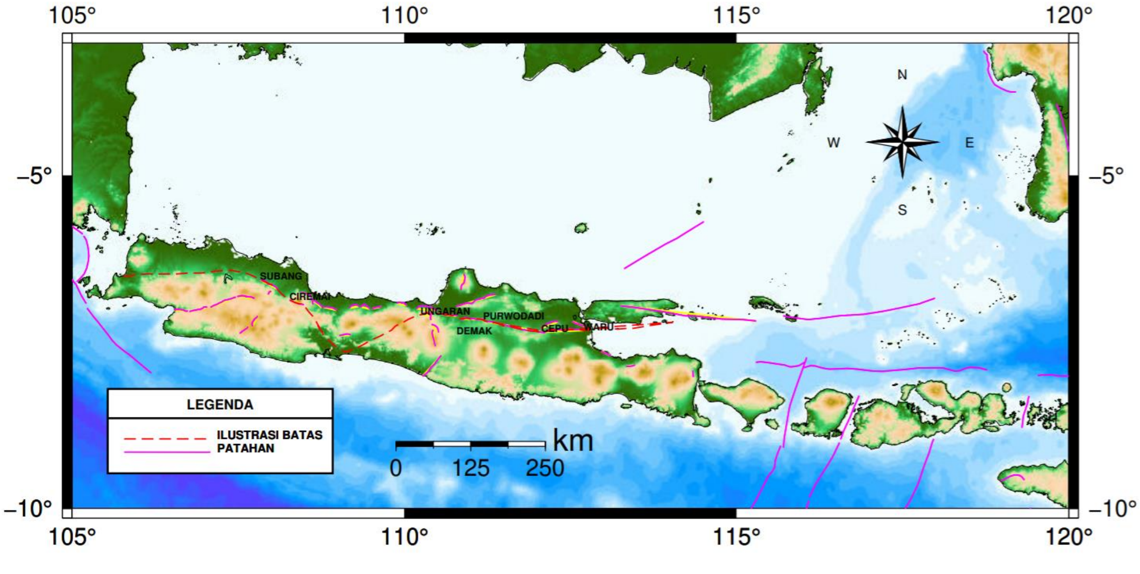

Figure 7. Illustration of the Sunda Plate Boundary in Java Island

In Figure 7. there is a dashed line in red that illustrates the boundary of the Sunda Plate in Java Island. From the identification results in this study, the boundary is analyzed based on geodetic data, seismic data, and geological structure data of Java Island. The geodetic data analysis described earlier explains that the Sunda plate boundary in Java Island is an active fault on the mainland of Java Island. This is evidenced by the resulting velocity vector residue, the obtained Euler rotation parameter value, and supported by seismicity data, and the geological structure of Java Island. The boundaries of the Sunda plate on the island of Java are active faults on the mainland of Java, including the Baribis-Kendeng Fault (Subang, Demak, Purwodadi, Cepu, and Waru Segments), Ciremai Faults, and Ungaran Faults.

* DISCUSSION

1. Analysis of Euler Parameter Estimation Results

Furthermore, the resulting block model's residual velocity vector can be analyzed by the existing deformation phenomena (Figure 4), the red arrow is the residual velocity vector, and the error ellipse scale of 1 mm. In figure 4, it can be seen that the majority of velocity vectors in Java Island move towards the north. There is a residual velocity vector of movement in the western part of Java that points east and northeast, except for the CROL station moving towards the southwest. Then in the Central Java section, the three stations show different directions. The CCIR station moves westward, the CPKL station moves southwest, and the CPBL station moves towards the Southeast. This is due to intra-block deformation due to the movement of local faults in the area (Kuncoro, 2013). At the beginning of defining the boundary of the Sunda Plate, based on block modeling theory, the fault that is on the land side of Java Island is the possible final boundary for the Sunda Plate, then looking at the residual velocity vector in the south of the fault namely the CPBL station shows that its movement is towards the South of Java, it is shown that the boundary of the Sunda Plate on the island of Java has an arch boundary that is more to the south.

2. Analysis based on Seismicity Data and Geological Structure of Java Island

Seismicity data for tectonic earthquakes were obtained from the United States Geological Survey (USGS) from 1934 to 2020 with a depth of 0 to 40 kilometers. The data received consists of the time of the incident, geographic latitude and longitude, and the epicenter's depth. And the strength of the earthquake or Magnitude Body (M.B.). Meanwhile, the number of recorded earthquakes was 37. The analysis using seismic data based on the USGS catalog was carried out by considering the seismic data obtained from the USGS has a more extended period than the data obtained from the Meteorology, Climatology and Geophysics Agency (BMKG). Also, the USGS seismograph station has sensors that are far from the epicenter. When the sensor from the seismograph is far from the epicenter location, the body waves (primary) and surface waves will be recorded clearly without any other vibrations (noise), seismotectonic map, or distribution tectonic earthquakes based on their strength is shown in Figure 8.

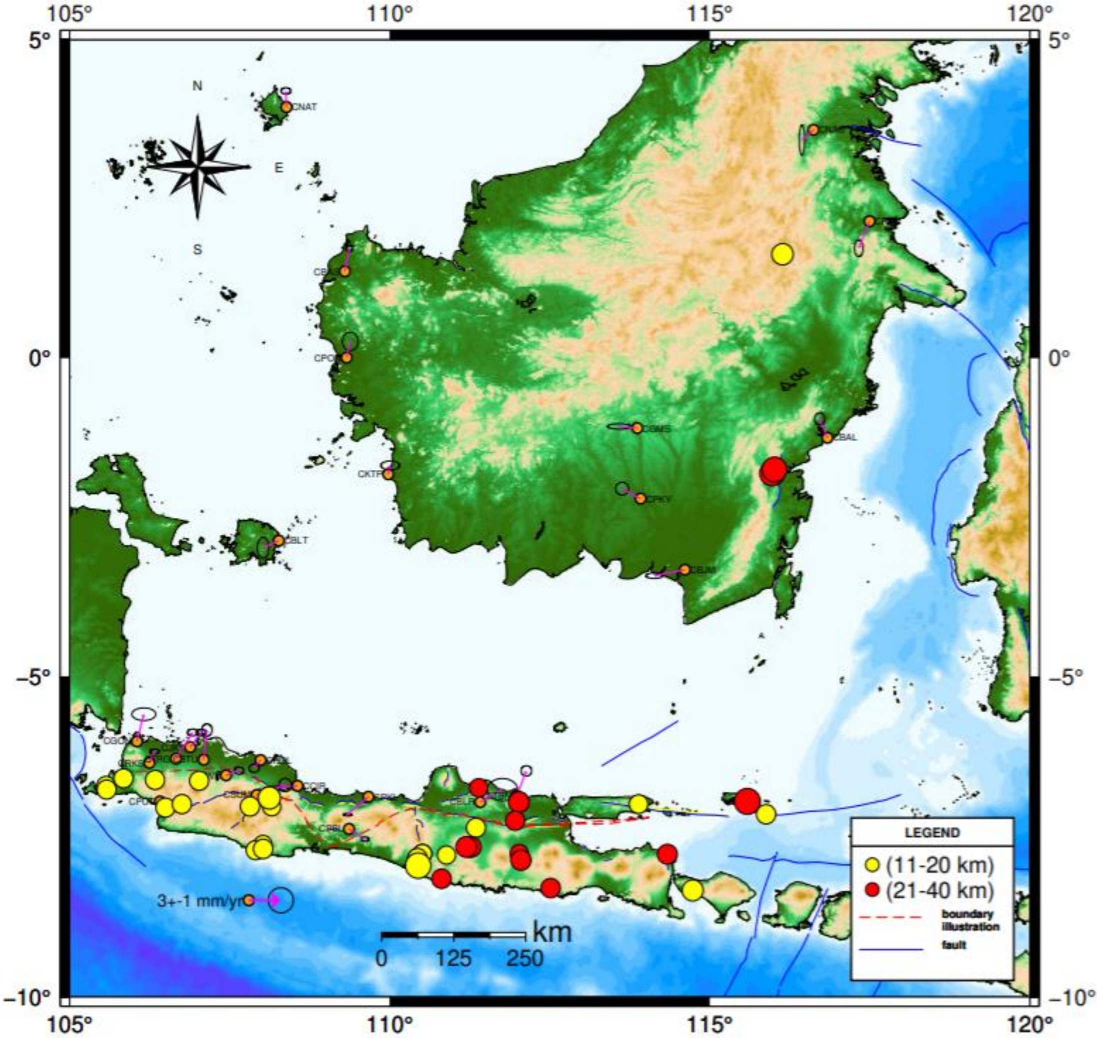

Figure 8. Distribution of Seismicity Data Based on the USGS Catalog

In Figure 8, the earthquake magnitude value is shown by the circle's size; the larger the circle, the greater the magnitude value. Most of the earthquakes in East Java occur at a moderate depth, in contrast to West Java earthquakes that occur at a shallow depth. Based on the seismic data in Figure 8, the amount of seismic activity in West Java and East Java indicates an active fault in the area. The accumulation of energy from the active fault causes a shallow earthquake in the area. Furthermore, it can be identified that the amount of seismic activity that occurs in the fault area allows that the boundary of the Sunda Plate in the Java Island is an active fault on the mainland of Java Island.

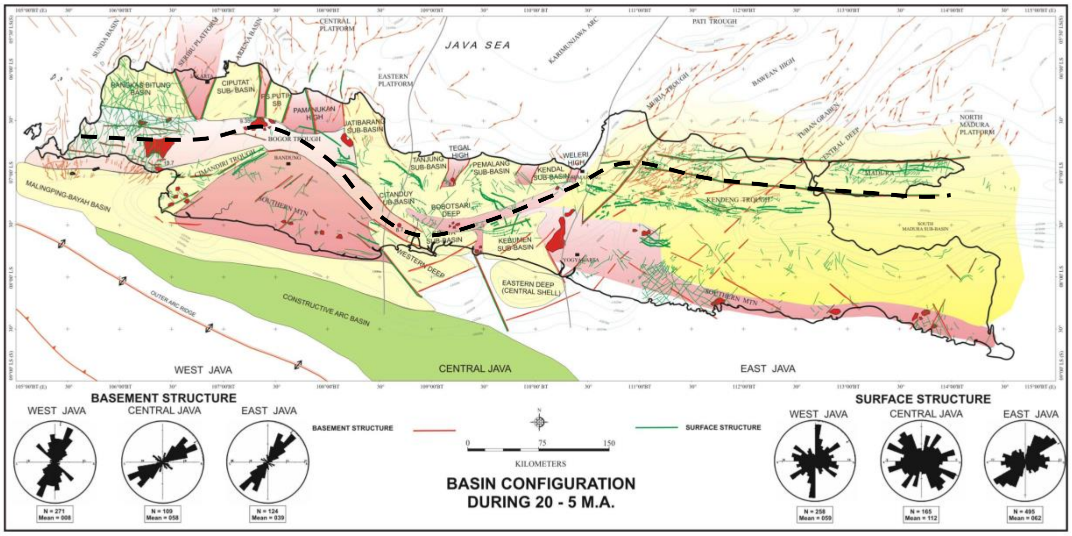

Figure 9. Geological Structure of Java Island
Source: Sribudiyani, et al, 2003

In addition to seismic data, geological structure data is also used to support analysis in identifying the Sunda Plate's boundaries on the island of Java. Figure 9 is a geological structure pattern in Java; the Bogor Basin represents the West's structural pattern. In the center, the pattern is represented by the North Serayu and South Serayu zones. It is indicated by the Kendeng Mountains Fault's direction, which is an upward fault to the east. The black dotted line in the image illustrates the geological structure pattern, which explains that there is a curve in Central Java. This curvature pattern supports geodetic data, which has previously been described that one of the stations located in the southern part of the fault in the Central Java part, namely the CPBL station, is still included in the Sunda Plate. Also, the basement structure and surface structure indicate a boundary between North Java and South Java, and this indicates that the Sunda Plate boundary in Java is an active fault on the mainland of Java Island, wherein the Central Java region, the boundary is further south.

* CONCLUSIONS

Based on the results of research that has been carried out, there are conclusions that can be drawn, namely that the final boundaries of the Sunda plate in Java Island are active faults on the mainland of Java Island including the Cimandiri Fault, the Baribis-Kendeng Fault (Segment Subang, Demak, Purwodadi, Cepu, And Waru), Ciremai Fault, and Ungaran Fault. This boundary is obtained properly from the residue vector in Java Island with a vector scale of 3 mm, and is supported by seismic data and the geological structure of Java Island.

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