Identification of Slip Distribution Mw 8.1 Biak Earthquake on February 17, 1996

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Abstract. On February 17, 1996, at 05:59:30 UTC there was an Mw 8.1 earthquake. Besides, it caused a tsunami. This event occurred in the northern part of the Cendrawasih Bay, where the New Guinea Thrust segment had a relatively low average slip velocity. To obtain a finite fault, waveforms from a tele-station located 30-90 degrees are used. The far-field body wave equation is used and inverted by the Kikuchi-Kanamori algorithm. In addition to obtaining source parameters, this study also aims to determine the value of the rupture velocity that occurs during coseismic events. From this research was found that the rupture velocity ($v_r$) was 2.5 km/s, which occurred at a depth of 13.7 km. The largest value of vector slip is 2.31 m, with an average slip value of 0.922 m. The dimension area of the fault has a size of 272 km x 110 km. The seismic moment obtained is $1.5 \times 10^{21}$ Nm, which is equivalent to Mw 8.1. This study also found a variance of 0.2844 in the use of the P and SH wave components, which is the smallest variance from the use of the P, P and SH, and SH components in the Kikuchi-Kanamori Program.

Keywords: slip, finite fault, asperity, rupture

1. Introduction

Major earthquake at 05:59 UTC on 17 February 1996 resulted in a tsunami as high as 7.7 meters [1]. This incident was a tsunamiogenic earthquake with a Mw magnitude of 8.0 with a rupture duration of 117 s [2]. The earthquake and tsunami incident killed 107 people [1]. The hypocenter of the Biak earthquake occurs at 0.67$^\circ$S 136.62$^\circ$E based on Global Centroid Moment Tensor Catalogue. Based on the hypocenter plot, on the north side of Cendrawasih Bay there were no earthquakes deeper than 100 km. This is consistent with the results of the study using the tomography method, which shows a gentle angle of support from north to south. The Micro-Caroline Plate, the Pacific sub-plate, which extends to the Australian Continent plate.

In previous research, it was found that the slip distribution model in the fault plane changes with time. Research conducted by Hanry and Das used an inversion algorithm to obtain slip and distribution values in the fault plane, as well as the application of SH components for a variety of solutions by Das and Kostrov [3,4]. While in this study using the Kikuchi and Kanamori algorithm [5-8].

The slip distribution having the same value on the fault plane will be connected by a line to form the contour of the plane. The area formed based on the line connecting the value greater than half the maximum slip is called asperity [9]. Asperity, the lock zone between fault planes, will be released when the main earthquake occurs [10]. Aftershocks occur slightly in asperity, but will occur in areas with small slip values [11].

2. Methods

The signal recording data used in this study were obtained from the Incorporated Research Institution for Seismology (IRIS) with the website address: http://ds.iris.edu/wilber3/find_event. The station used is a tele-station with a distance of 30$^\circ$-90$^\circ$ earthquakes. It is difficult to determine the correct order based on waveform matching alone. To see the effect of the iteration order on the solution, Kikuchi
and Kanamori introduced an additional procedure after the usual forward iteration [7]. To form synthetic waves, Green's function \( w_{jn}(t; p) \) is needed based on the basic moment tensor \( M_n \) [8]. Then for synthetic waveform \( y_j(t; p) \) based on the basic moment tensor can be found by

\[
y_j(t; p) = \sum_{n=1}^{N_h} a_n w_{jn}(t; p_1)
\]

(1)

The coefficients \( a_n \) and parameter \( p \) representing the onset time and location of the subevent are obtained by

\[
\Delta = \sum_{j=1}^{N_z} \int \left[ x_j(t) - \sum_{n=1}^{N_h} a_n w_{jn}(t; p_1) \right]^2 dt = \min
\]

(2)

\( \Delta \) is the residual error, \( N_z \) is the number of seismograms, and \( x_j(t) \) is the wave of observation. In the iteration process, hypocenter depth search is also carried out by searching the grid for \( p \). This is done in order to obtain the maximum correlation function \( \Psi(p) \) between observation waves and synthetic waves [8]:

\[
\Psi(p) = \frac{\sum_{j=1}^{N_z} \int [x_j(t)y_j(t; p)] dt}{\sum_{j=1}^{N_z} \int [x_j(t)]^2 dt}
\]

(3)

Then the source depth obtained from the inversion \( h \) is formulated [12]:

\[
h = h_0 + d_k \times (k_k - k_0) \times \sin(dip)
\]

(4)

\( h_0 \) is the reference depth, \( d_k \) the distance between the grids, \( k_k \) the corresponding grid points are identified, and \( k_0 \) is the reference point.

This study also compares the slip vector determination based on the type of wave component used in the inversion process. Henry and Das; Kikuchi and Kanamori; Kikuchi et al; and Kikuchi et al used the P and SH components to identify the slip distribution in the fault plane [3,7,8,13]. However, Yamanaka and Kikuchi used the P or SH component due to the limited waveform data from several earthquakes under 1960 studied [9,11]. In addition, this study compared three values of front rupture velocity \( v_r \). The purpose of comparing the results from the use of these three values is to determine the best slip vector and fault area based on the variance of the inversion process.

In this processing, 4, 6, and 7 time functions of the isosceles trapezoid source are used. The number of the source time function represents the number of subevent used which depends on the area of the fault plane. The source time function width varies and T1 is used at 3 seconds, 4 seconds, 5 seconds from the onset time of each subevent. The condition for the greatest energy release is assumed to last 4 seconds, so that T2 is worth 7 seconds, 8 seconds, and 9 seconds. The length of the upper and lower sides of the isosceles trapezoid is fixed but the height varies depending on the seismic moment value of the subevent. All seismic moments from the subevent are combined, into a seismic moment value and show the source time duration of the earthquake event in this study.

3. Results
The results of processing using USGS depth parameters obtained strike value = 103°, dip = 11°, average rake = 69°, and the largest slip was 2.31 m with an average slip of 0.922 m. The new hypocenter obtained after processing was at a depth of 13.7 km. The amplitude obtained is \( M_w \) 8.05 (~\( M_w \) 8.1) and the seismic moment is \( 1.55 \times 10^{21} \) N.m. While the duration of the source time obtained
from this processing is 100 seconds which is seen in the source time function curve (Figure 1). The greatest energy release occurs at 40 seconds after the initial burst. The results of processing using the USGS depth parameter have a variance value of 0.2844.

The dimension of the fault plane in this processing is almost the same as USGS fault plane parameter, it was 29,920 km². The maximum rupture velocity is 3.2 km/s based on the value of the S wave velocity at a depth of 20 km in the Papua region. The result of the slip vector distribution in the fault plane is transformed from the XY-local coordinates of the fault plane to geographic coordinates (Figure 2). Based on the previous processing wave fitting (Figure 3), the body waves used are 15 P components and 6 SH components from 15 bandpass filtered recording stations in the range of 0.006 Hz to 0.1 Hz.

Figure 2 shows the distribution of the value and direction of the slip vectors in the fault plane during the 1996 Biak earthquake. It can be seen that the hypocenter is not at the largest slip value or the asperity zone. This reinforces that the part of the fault plane that experiences a fault is not the strongest part but in a weaker area. It triggers a part that is locked tightly and that's when the seismic energy is emitted the most. The total source time function graphic shows the time of energy release during coseismic. The largest energy release is indicated by the largest amplitude of the graph.
Figure 2. Model of Slip Vector Distribution in The Fault Plane.

Figure 3. Fittings of The Observation Wave (Red) with Synthetic Waves (Black) Using The USGS Depth Parameter.
The results of this study use two depth parameters, then the best is selected quantitatively based on the variance value. After that, it is compared again with the processing results using the P component and the SH component. In this study also compared the front rupture rate ($v_r$). The aim is to determine the area of the fault plane and the best slip vector value from the Biak earthquake based on the far-field body wave inversion method. The processing results are shown in Table 1 which shows the value of the source parameter, magnitude, depth, and variance value of each processing. Based on the variance value, the results of processing using the depth parameter of the USGS, the P and SH wave components, and the use of a front rupture velocity of 2.5 km/s get the best results with a variance value of 0.2844.

This study also tested the use of the body wave component and the rupture velocity that was entered as inversion data. The use of the P and SH components together gets the smallest variance (best result). However, in some cases only P or SH components are used due to limited waveform data from several earthquakes before 1960 studied [9,11].

In shallow earthquake depths, the Kikuchi-Kanamori Program is more difficult to obtain $M_w>8$ because if the area of the fault plane and the front rupture velocity ($v_r$) are not correct, the inversion will be bad and the results do not match the actual situation. The use of front rupture velocity values of 1.5 km/s, 2.0 km/s and 2.5 km/s refers to the research of Gusman et al [14]. However, in this study, the seismic data were converted with GPS data and tsunami data records, so the results of the processing could not be compared. Using a front rupture velocity ($v_r$) of 2.5 km/s, the smallest variance is obtained. The $v_r$ value that obtained corresponds to research on the Mentawai earthquake 2007 $M_w$ 8.4, which has a magnitude similar to the 1996 $M_w$ 8.1 Biak earthquake, namely $2.1 \pm 0.4$ km/s [15]. Konca et al used the front rupture velocity ($v_r$) in the range of 2.1 km/s to 2.8 km/s to identify the slip vector distribution in the 2007 $M_w$ 8.4 Mentawai earthquake [15]. However, the Mentawai earthquake occurred at a depth range of 20-30 km [15,16].

4. Discussion

The processing results show the source parameters and the finite fault model. The use of two depth parameters (shallow and deep), three types of inversion based on wave components (P, P and SH, and SH), and three values of front rupture velocity ($v_r$) aim to obtain the best source parameters from the processing results. The results of this study obtained various hypocenter depths (Table 1). The use of the initial parameters of hypocenter depth, fault plane dimension, and front rupture velocity ($v_r$) influenced the new hypocenter depth inversion result. In processing using $v_r$ 2.0 km/s, the depth of the inversion result was 14.3 km. The depth of the inversion result is different from the inversion result using the P, P and SH, and SH wave components. In fact, all processing uses the USGS depth parameter, which is 20 km. This shows that using different wave components does not affect the depth of the inversion. However, the use of the wave component in the inversion process affects the slip vector and the variance value.

The identifications of slip vectors in the finite fault model using the P and SH components have a wave fitting shape that appears to have a lower match than using only P or SH components. The low suitability of the waves indicates that the resulting fault plane has high heterogeneity, so that it can identify the location of the asperity well [11]. In addition, when viewed based on the variance value, the use of P and SH components has the best results. In this study, the variance value of the use of the components P (0.5117), P and SH (0.2844), and SH (0.3632) was obtained. The variance value is consistent with research conducted by Amini et al who got the variance value of the use of the P (0.6), P and SH (0.29), and SH (0.28) components [17].

The selection of the best results from the resulting model based on quantitative and qualitative analysis refers to previous research. The results of this study are also compared with previous research conducted by Henry and Das and research in the USGS catalog [3]. The biggest difference between this processing result and previous research is the largest slip value. The solution obtained is stable and in accordance with the data but does not guarantee that the solution is in accordance with the
actual slip [19]. A comparison of the results of this processing with Henry and Das and those in the USGS catalog is shown in Table 1 [3].

| Model         | Strike | Dip  | Rake  | Slip Max. | Average Slip | Mag. (Mw) | Depth  |
|---------------|--------|------|-------|-----------|--------------|-----------|--------|
| This study    | 103°   | 11°  | 69°   | 2.31 m    | 0.922 m      | 8.05      | 13.7 km|
| Henry dan Das | 109°   | 9°   | 72°   | 12 m      | 4 m          | 8.2       | 10 km  |
| USGS          | 109°   | 17°  | 67°   | 8.385 m   | 1.130 m      | 8.1       | 20 km  |

The validation use of empirical equations and the distribution of aftershocks still has a relatively high value of subjectivity. For this reason, this study uses the results of ground motion observations using Global Positioning System (GPS) measurements as validation of the results of this research. Michel et al conducted research on the movements of the earth's crust in East and Southeast Asia using GPS measurements [18]. GPS measurements originate from the GEODYSSSEA Station which records deformation due to earthquakes during the period 1994-1998 (Figure 4).

![Figure 4. Vector Showing Deformation After The 1996 Biak Earthquake with 6° Azimuth at Coseismic (Full Seismic Coupling) Shown by Red Arrows [18]](image-url)

The slip direction of the 1996 Biak earthquake had an azimuth of 6° when coseismic and interseismic were recorded by GPS measurements. The results of this study get strike = 103° and rake = 69°, so that the azimuth vector slip is 8°. This shows that the results of this study are in accordance with GPS observations.

5. Conclusion
The Biak Tsunamigenic earthquake of February 17, 1996 was an up-dip type (direction of slip to the surface). The earthquake source mechanism parameters obtained from the inversion were $M_w$ 8.05 (~$M_w$ 8.1) with a strike value = 103°, dip = 11°, and an average rake = 69° that occurred at a depth of
13.7 km. The dimension of the fault plane that has undergone a shift is 272 km x 110 km. The maximum slip value of the 1996 Biak earthquake was 2.31 m with an average slip of 0.922 m and rupture velocity ($v_r$) was 2.5 km/s along the fault plane. The process of identifying the earthquake source mechanism, especially in the finite fault model, is better to use broadband signal data with the use of P and SH components. The use of the P and SH components in the Kikuchi-Kanamori Program obtained the smallest variance value.

Author Contributions
All authors have reviewed the contents of the manuscript and approved it for publication.

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