# Appendix 2: Obtaining the Rupture Plane from Aftershock Sequences

## Methodology

The catalogue used for fitting the rupture plane from the aftershock sequences includes observed events that occurred within 20 km of the mainshock epicentre (-37.506°, 146.402°) from the time of the mainshock until 30 April 2024. The method for rupture plane identification involves dataset preparation, plane fitting, and fault plane identification (Figure S3).

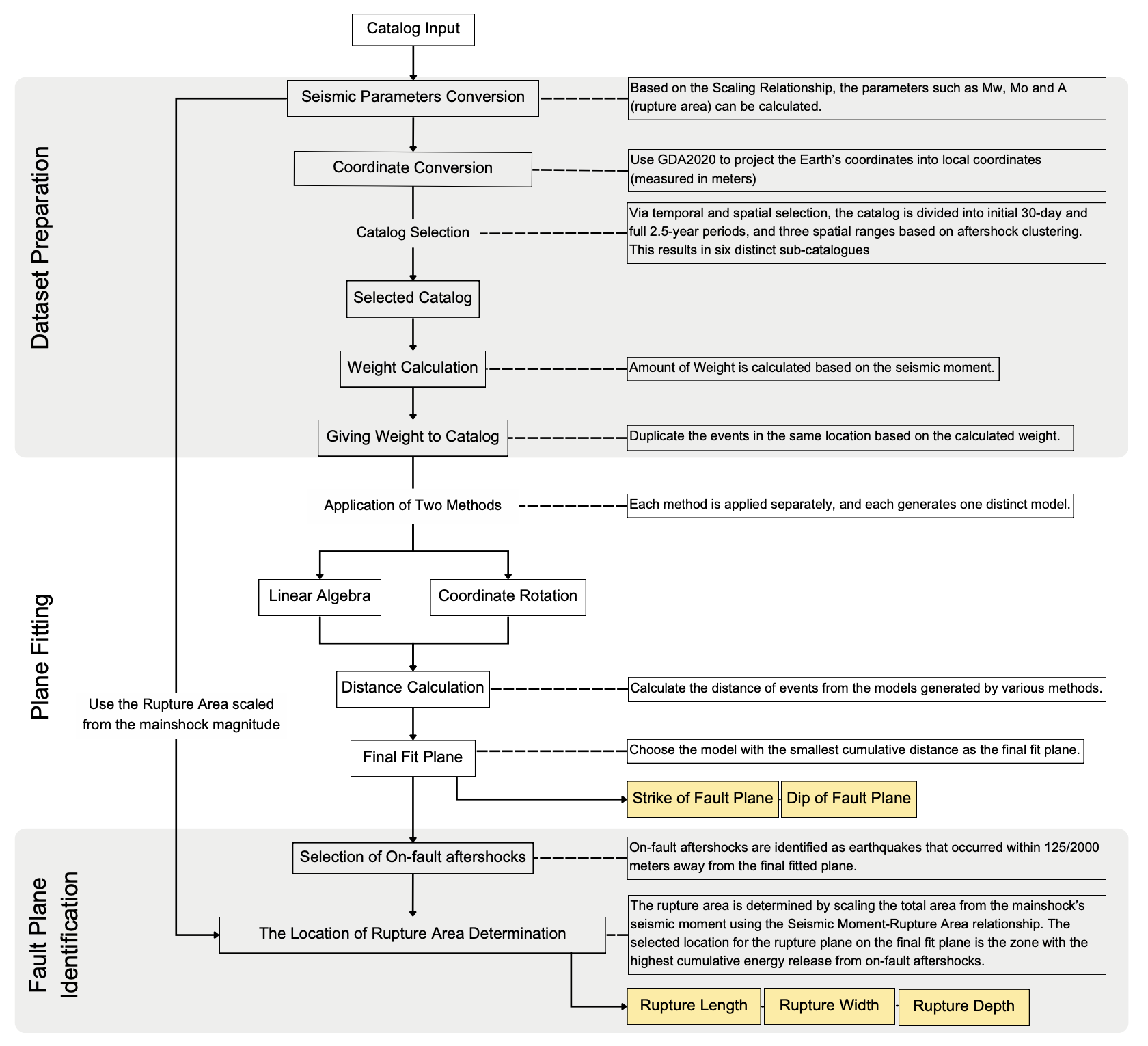


Figure S3. A summarized schematic of the methodology for obtaining rupture plane from the aftershock sequence.

**1 Dataset Preparation**

The energy released from the aftershocks will be analysed only within the near-focus region. Therefore, a catalogue with a 20 km radius covering the period from the mainshock to April 30th, 2024, will be used. After inputting the catalogue, the next step is parameter conversion.

* 1. **Seismic Parameters Conversion.**

The raw dataset was provided by the Seismology Research Center (SRC), which relocated the earthquake locations using data from seismometers. The catalogue from SRC includes the occurrence time, location (latitude, longitude, and depth), and local magnitude of each event. For the subsequent analysis, the required seismic parameters are moment magnitude (MW), seismic moment (MO), and rupture area (A). These parameters will be calculated using scaling relationships. The conversion of events to moment magnitude (MW) will be performed using Equation S1.

Seismic Moment (MO): From moment magnitude (MW) to seismic moment (Hanks & Kanamori,1979).

Equation S3

Rupture Area (A): From seismic moment (MO) to rupture area (A). For stable continents, Somerville (2021) proposed the following equation to represent the scaling relationship between seismic moment and rupture area:

Equation S4

* 1. **Coordinate Conversion**

To ensure consistency and accuracy in analyzing the geometry of the aftershock spatial distribution, it is crucial to maintain uniformity in coordinate units. We use meters as the standard unit to avoid distortions in the point cloud structure, which helps minimize calculation errors and maintain spatial integrity. To convert from Earth coordinates to a meter-based coordinate system, we utilized the MATLAB function *projcrs*, which accurately projects latitude and longitude coordinates into the EPSG:7899 (GDA2020) system.

* 1. **Dataset Selection**

The original dataset encompasses a 20 km radius around the mainshock epicenter (Figure S4A) and covers a period of 2.5 years, from the mainshock up to April 30, 2024. The point map (Figure S4C) visually represents the clustering of aftershock sequences. Based on the density map, the dataset was stratified into three spatial ranges (Table S1) to assess the effects of both high clustering degrees and wider-range seismicity.

Table S1. Six subcatalogues were created based on temporal and spatial constraints separately. The spatial division was done by categorising the catalogue into three subranges, according to the degree of aftershock clustering observed on the point density map (Figure S4). For example, Dataset 1 includes earthquakes that occurred within the first 30 days following the mainshock and within spatial range 1. These six datasets will be used for further analysis in the subsequent steps.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | |  |  | **Time** | |
| **Space** | **Range** | **Latitude (o)** | **Longitude (o)** | **Initial 30 days** | **Since Mainshock to 30/04/2024** |
| **1** | -37.54 ～-37.47 | 146.38 ～ 146.42 | Dataset 1 | Dataset 4 |
| **2** | -37.55 ～-37.45 | 146.35 ～ 146.44 | Dataset 2 | Dataset 5 |
| **3** | -37.68 ～-37.33 | 146.18 ～ 146.58 | Dataset 3 | Dataset 6 |

A screenshot of a map

Description automatically generated

Figure S4. The spatial distribution of aftershock sequences is illustrated in Figures A to D. Figures A and B present the aftershock distribution in map view, while Figures C and D display the aftershock density map. The density map was generated by dividing the area into 200x200 rectangular grids, counting the frequency of events per cell, and assigning colours based on the density, as indicated by the colour bar on the right. Both Figures B and D include spatial slices based on point density. Range 1 highlights the most clustered area, Range 2 encompasses a broader area with the majority of aftershocks, and Range 3 covers the entire 20 km radius from the mainshock, with no spatial constraints on the original dataset.

In line with Omori's law (1894), which posits that most aftershock sequences occur shortly after the mainshock, we partitioned the dataset into two subcatalogues: one covering the initial 30 days and another comprising the full dataset without temporal constraints. By applying both time and space filtering criteria, we generated six distinct catalogues (Table S1) which will be used to identify the rupture plane.

* 1. **Weight Calculation**

The weighted method is applied, scaling from the minimum seismic moment (MO) in the catalogue, calculated during the seismic parameter conversion step. Events are then duplicated at their respective locations based on their weight. This approach helps to prevent aftershock clustering from obscuring fault geometry. The surrounding rock near the mainshock experiences higher energy release, leading to more frequent displacements and fractures (Torabi et al., 2020), which significantly influence aftershock distribution (Yukutake & Iio, 2017). Thus, the weighted method is used to accurately highlight the aftershock spatial distribution in relation to the mainshock.

**2 Plane Fitting**

We assume the fault plane generated from the aftershock sequences forms a rectangular plane in 3D space. Despite location uncertainties of up to 2 km (Neo et al., 2021), we consider the aftershock locations in the SRC dataset accurate. This assumption is supported by the use of a relatively complete and accurate dataset, with earthquake locations having been relocated prior to our analysis.

* 1. **Linear Algebra**

In the context of linear algebra, extending the least squares method from 2D to 3D involves fitting a plane to a set of points rather than a line. In 3D space, the general equation for a plane is given by:

Equation S5

Where , , and are longitude, latitude, and depth depending on the calculation being performed. The coefficients matrix (Equation S6) should be solved to find the best-fit plane using the least squares method.

Equation S6

The relationship between , and can be rewritten as:

Equation S7

To solve for coefficients, the matrix equation is used as:

Equation S8

The results of fitting a plane using linear algebra can vary based on the identification of independent variable axes, which influences the error at each point. To ensure the best fit regardless of coordinate changes, three calculations are performed, and the plane with the smallest overall distance is selected (Figure S5).

A diagram of a model

Description automatically generated

Figure S5. This schematic summarizes the linear algebra method. Beginning with a pre-processed catalogue as input, the least squares method is applied to three variations of the plane equation, each representing a different format. The best-fit plane is determined by the smallest cumulative perpendicular distance from the events.

* 1. **Coordinate Rotation**

Referring to the established fault planes, the fault plane is inferred to be nearly vertical (e.g., 87o dip - Mousavi et al., 2023). Due to the spatial correlation between aftershock distribution and fault plane geometry, their surface projection is expected to exhibit linear characteristics, reflecting the fault plane's projection. Before performing coordinate rotation, it is essential to determine the 'strike' by projecting events onto the surface and identifying the regression line that best fits the 2D point distribution. The angle between this line and the y-axis approximates the fault plane's strike.

Coordinate rotation is then performed based on the fault structure's geometry. The entire point cloud is rotated by the angle of the 'strike,' while keeping the depth axis unchanged. The rotation point is determined as the centroid of the aftershocks (unweighted point cloud on the surface), rather than the origin of the meter coordinates or the mainshock epicenter. This adjustment accounts for potential deviations of the aftershock cloud from the mainshock epicenter, especially in cases of a unilateral rupture plane. However, since this rupture plane is bilateral (Quigley et al., 2021), the centroid of the aftershock unweighted cloud closely approximates the mainshock epicenter (Figure S6).

A graph with green dots and black lines

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Figure S6. An example of coordinate rotation: The regression line fitted to the aftershock epicenter distribution represents the fault plane's projected line on the surface. The longitude-latitude coordinate system is then rotated around the revised origin point (the average location of the aftershock sequence, marked by the yellow star in the figure) until it aligns parallel with the regression line. The black dashed line illustrates the rotated coordinate system.

After rotation, the next step is to determine the 'dip' by fitting a regression line in the vertical plane. Events are projected onto the rotated x-axis, aligning it with the dip direction to create a depth plane. A regression line is then fitted on this vertical plane, representing the roughly linear relationship between the depths and the dip direction of the fault plane (Figure S7).

Figure S7. The geometry of strike-slip fault structure.

The final step involves determining the orientation of the fault plane and deriving its equation by identifying three key points:

a) The first point is located at the intersection of the horizontal regression line, extended in depth, with the vertical regression lines. This intersection point, which lies on the fault plane, is used as the initial reference.

b) The second point is situated on the surface regression line and must also be on the fault plane.

c) The third point is the centroid of the earthquake point cloud. In the case of a weighted point cloud, this corresponds to the location of the mainshock hypocenter.

With these three points identified, the orientation of the fault plane can be established. The strike of the fault plane is determined as the angle between the horizontal plane and the fault plane, while the dip is the angle between the vertical plane and the fault plane. Additionally, the distance of each event from the fault plane can be computed.

* 1. **Distance Calculation**

To calculate the distance of each seismic event from the fault plane in 3D space and to select the most appropriate plane for describing the aftershock distribution, the point-to-plane distance formula (Equation S9) was employed.

Equation S9

Where () are the coordinates of the events, and assuming the plane equation is , and is the perpendicular distance from the event to the plane.

* 1. **Selection of the Final Fit Plane**

To determine the optimal fit plane for the dataset, the cumulative distance calculated using each method (linear algebra and coordinate rotation) is evaluated. The method that yields the minimum cumulative distance is selected, as it indicates the best fit for the dataset. It is important to note that the final fit plane obtained from this step represents the orientation of the fault plane but does not specify its dimensions. This fit is conceptualised as an infinite plane that provides insight into the fault plane's orientation (i.e., dip and strike). The specific dimensions of the fault plane will be determined in the subsequent step by analysing the area of rupture and the distribution of on-fault aftershocks.

1. **Fault Plane Identification**

**3.1 Classification of On-fault Aftershocks**

On-fault aftershocks are defined as earthquakes that occur along the mainshock’s fault plane. The width of the damage zone can range from 200 to 250 meters, as observed in events such as the 1992 Mw 7.3 Landers earthquake (Peng et al., 2003), the 2010 Mw 7.1 Darfield earthquake (Li et al., 2014), and the Parkfield segment of the San Andreas Fault (Lockner et al., 2011), with variation depending on the specific fault. Consequently, aftershocks occurring within 125 meters of the final fit plane are considered on-fault aftershocks.

However, Churchill et al. (2024) addressed uncertainties in seismic event locations and fault geometry complexities by setting a maximum cutoff distance of 5 km (2.5 km on each side of the best-fit plane) for identifying on-fault aftershocks. Since their study focused on mainshocks with Mw 6.0 (e.g., the 2004 Mw 6.0 Parkfield and 2014 Mw 6.0 South Napa earthquakes), we have adjusted our cutoff distance to 4 km (2 km on each side of the final fit plane) for our analysis.

* 1. **Location of Rupture Plane**

To facilitate the calculation of distances from events to the fit plane, the meter coordinates were rotated to align with the fit fault plane (Figure S8). The rotation procedures are as follows:

**Initial Rotation:**

a) Maintain the depth coordinate unchanged.

b) Rotate the coordinate system to align with the strike and dip directions, as determined from the final fit plane. Consequently, the previous longitude axis becomes the dip direction axis, and the latitude axis becomes the strike axis.

**Second Rotation:**

a) Preserve the strike axis unchanged.

b) Rotate the coordinate system to align with the down-dip rupture direction. In this alignment, the previous depth coordinate is reoriented to become the down-dip rupture axis, and the dip direction axis is adjusted to become perpendicular to the down-dip rupture axis in the vertical plane.

**A collage of different angles

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Figure S8. This schematic summarizes the method for rotating the meter coordinates to align with the final fit plane. The pink plane represents the final fit plane selected from the previous steps. The entire coordinate system is rotated to align with this final fit plane. The distance of events from the final fit plane is eventually converted to the distance from the strike-down-dip-rupture coordinate plane (which is vertical in the rotated coordinates). (1) Figures A to B show the first rotation, which occurs in the horizontal plane (longitude-latitude plane). The rotation angle is the strike angle. (2) Figures B to C show the second rotation, based on the first rotated coordinates. This rotation occurs in the vertical plane, keeping the strike axis unchanged. The dip angle rotates the depth and dip direction axes to align with the final fit plane. (3) Figure D shows the final rotated coordinates aligning with the final fit plane. (4) Figure E compares the original coordinate system with the final rotated coordinate system. (5) Figure F illustrates the process of coordinate rotation, combining Figures A to D.

Following these two rotations, the coordinate system is aligned parallel to the final fit plane. The fault plane identification is then based on this rotated coordinate system. The area of rupture, determined in a previous step and scaled from the mainshock moment magnitude, is assumed to be rectangular. This area is calculated as the product of length and width (Equation S10).

Equation S10

Where is the area of the fault plane during the mainshock stage, is the length of the fault plane, and is the width of the fault plane. We assume that the on-fault aftershocks identified before (i.e., earthquakes occurring within a maximum of 125 m or 2 km on each side of the final fit plane) occur on the final fit plane for each dataset. Then, under the framework of the equation above, we find the area with the maximum cumulative energy released from on-fault aftershocks that meets the rupture area limitation. The rupture length and width will be determined in this step. To determine the maximum and minimum rupture depth of the plane, rotate the coordinate system back to its original orientation to locate the rupture plane in meter coordinates.

After identifying the fault plane, the average slip can be calculated for the plane by combining Equation S10 and Equation S11.

Equation S11

Where is the shear modulus of the rock, is the rupture area and is the average slip on the fault plane. The value of used for this study is 3 x 1011 dynes/cm2, which is a reasonable value according to Kayal (2006).

## Results and Discussion

**1 Final Fit Plane**

The results obtained from the linear algebra method are shown in Table S2. The best-fit plane for each dataset, determined through various calculations and formats of plane equations, is highlighted in bold and italicised. A comparison with the best-fit results from other method is presented in Table S3.

Table S2. The results of the linear algebra plane fitting process. The inclined and bold words indicate the model with the best residual (i.e., the minimum cumulative distance) for each dataset. This model will be compared with those obtained from the coordinate rotation method to determine the best-fit plane for each dataset.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Dataset** | **Weighted Method?** | **Depth =**  **f(Longitude, Latitude)** | | | **Latitude =**  **f(Longitude, Depth)** | | | **Longitude =**  **f(Latitude, Depth)** | | |
| Strike | Dip | Sum of Distance | Strike | Dip | Sum of Distance | Strike | Dip | Sum of Distance |
| **Dataset 1** | No | 112.7 | 30.22W | 1.51E+06 | 291.68 | 84.82W | 8.29E+05 | ***354.93*** | ***88.58E*** | ***4.04E+05*** |
| Yes | 81.81 | 12.14E | 4.13E+08 | 292.9 | 85.45W | 2.62E+08 | ***357.31*** | ***89.48E*** | ***7.03E+07*** |
| **Dataset 2** | No | 96.59 | 15.24W | 2.22E+06 | 280.04 | 85.05W | 1.32E+06 | ***355.1*** | ***88.86W*** | ***8.48E+05*** |
| Yes | 66.65 | 24.95E | 4.46E+08 | 284.07 | 84.83W | 3.11E+08 | ***352.83*** | ***84.86E*** | ***1.42E+08*** |
| **Dataset 3** | No | 93.49 | 5.11W | 2.63E+06 | 282.35 | 86.15W | 2.09E+06 | ***351.81*** | ***87.7W*** | ***1.54E+06*** |
| Yes | 91.25 | 3.75W | 5.24E+08 | ***293.07*** | ***85.71W*** | ***3.84E+08*** | 320.43 | 87.55W | 9.35E+08 |
| **Dataset 4** | No | 100.84 | 21.53W | 2.34E+06 | 288.71 | 84.77W | 1.30E+06 | ***355.28*** | ***89.21W*** | ***6.67E+05*** |
| Yes | 85.21 | 7.81E | 5.12E+08 | 293.61 | 87.2W | 3.66E+08 | ***355.49*** | ***89.56E*** | ***1.48E+08*** |
| **Dataset 5** | No | 86.26 | 14.6E | 3.40E+06 | 279.26 | 84.22W | 2.19E+06 | ***354.75*** | ***89.13E*** | ***1.59E+06*** |
| Yes | 65.45 | 25.5E | 5.77E+08 | 286.42 | 86.44W | 4.40E+08 | ***350.76*** | ***84.18E*** | ***2.51E+08*** |
| **Dataset 6** | No | 87.01 | 3.18E | 4.22E+06 | 285.56 | 88.32W | 4.18E+06 | ***351.17*** | ***87.43E*** | ***3.14E+06*** |
| Yes | 68.69 | 24.15E | 1.16E+09 | ***256.08*** | ***70.77E*** | ***9.67E+08*** | 306.85 | 41.52E | 1.90E+09 |

Table S3. the final best-fit plane results for each dataset. The inclined and bold words highlight the model with the minimum residual (i.e., the smallest cumulative distance), indicating the final best-fit plane for each dataset.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Dataset** | **Weighted Method?** | **Linear Algebra** | | | **Coordinate Rotation** | | |
| Strike | Dip | Sum of Distance | Strike | Dip | Sum of Distance |
| **Dataset 1** | No | ***354.93*** | ***88.58E*** | ***4.04E+05*** | 357.04 | 89.58E | 4.15E+05 |
| Yes | 357.31 | 89.48E | 7.03E+07 | ***356.93*** | ***88.69E*** | ***6.28E+07*** |
| **Dataset 2** | No | ***355.1*** | ***88.86W*** | ***8.48E+05*** | 357.3 | 89.28E | 8.64E+05 |
| Yes | 352.83 | 84.86E | 1.42E+08 | ***350.85*** | ***83.2E*** | ***1.16E+08*** |
| **Dataset 3** | No | 351.81 | 87.7W | 1.54E+06 | ***352.62*** | ***85.96W*** | ***1.54E+06*** |
| Yes | 293.07 | 85.71W | 3.84E+08 | ***290.25*** | ***61.68E*** | ***3.56E+08*** |
| **Dataset 4** | No | ***355.28*** | ***89.21W*** | ***6.67E+05*** | 356.52 | 89.76W | 6.71E+05 |
| Yes | 355.49 | 89.56E | 1.48E+08 | ***355.1*** | ***88.25E*** | ***1.14E+08*** |
| **Dataset 5** | No | ***354.75*** | ***89.13E*** | ***1.59E+06*** | 355.56 | 86.99E | 1.60E+06 |
| Yes | 350.76 | 84.18E | 2.51E+08 | ***348.37*** | ***81.87E*** | ***2.00E+08*** |
| **Dataset 6** | No | ***351.17*** | ***87.43E*** | ***3.14E+06*** | 342.28 | 73.96E | 3.25E+06 |
| Yes | ***256.08*** | ***70.77E*** | ***9.67E+08*** | 277.23 | 80.35W | 1.27E+09 |

**2 Rupture Plane**

By applying the weighted method, we account for stress changes that influence the spatial distribution of aftershock magnitudes, thereby enhancing the geological significance of the best-fit plane. Consequently, the rupture plane identification is based on the final fit plane obtained using this method. The fault planes from datasets 1, 2, 4, and 5 generally strike close to the north-south direction. In contrast, the planes from datasets 3 and 6 exhibit different orientations (Figure S9 and Figure S10). Notably, the plane from dataset 6 has a relatively shallower dip angle, which can be attributed to the presence of large-magnitude aftershocks (i.e., ML 4.7). Specifically, two aftershocks with magnitudes greater than 4 were recorded up until April 2024: ML 4.2 and ML 4.7. Dataset 3 includes only the ML 4.2 event, while dataset 6 includes both the ML 4.2 and ML 4.7 events. The weighted method tends to align the plane with larger-magnitude aftershocks, thus skewing the orientation towards these events and deviating from the overall spatial distribution of aftershocks. Since datasets 3 and 6 are dominated by large-magnitude aftershocks, which may skew the analysis and not fully represent the aftershock cloud distribution, fault plane identification will rely on datasets 1, 2, 4, and 5. The rupture plane information obtained from these datasets is detailed in Table S4 and Figure S11.

A diagram of a diagram of a data set

Description automatically generated with medium confidence

Figure S9. The final fit planes from the weighted method. Only two aftershocks in the entire dataset have magnitudes larger than 4: an ML 4.2 event that occurred approximately 20 minutes after the mainshock, marked with a blue star; and an ML 4.7 event in June 2024, marked with a green star.

A graph of a graph of a number of particles

Description automatically generated with medium confidence

Figure S10. Location of aftershocks with ML larger than 4.0, from the mainshock until April 2024.

Table S4. Location of the fault plane results. Each dataset presents two sets of results for its fault plane location due to varying definitions of on-fault aftershocks: one with a width of 250 meters (125 meters on each side from the final fit plane), and the other with a width of 4 km (2 km on each side from the final fit plane).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Dataset** | **Final Fit Plane** | | **Fit Method** | **On-fault Range?** | **Rupture Plane** | | | |
| Strike | Dip | Length (Km) | Width (Km) | Min. Depth (Km) | Max. Depth (Km) |
| **Dataset 1** | 356.93 | 88.69E | Coordinate Rotation | DZ | 6.60 | 6.77 | 8.63 | 15.40 |
| 4Km | 6.20 | 7.20 | 7.63 | 14.84 |
| **Dataset 2** | 350.85 | 83.2E | Coordinate Rotation | DZ | 6.10 | 7.32 | 8.25 | 15.52 |
| 4Km | 6.20 | 7.20 | 7.68 | 14.83 |
| **Dataset 4** | 355.1 | 88.25E | Coordinate Rotation | DZ | 4.80 | 9.31 | 8.52 | 17.82 |
| 4Km | 5.80 | 7.70 | 8.82 | 16.52 |
| **Dataset 5** | 348.37 | 81.87E | Coordinate Rotation | DZ | 5.90 | 7.57 | 8.36 | 15.86 |
| 4Km | 6.10 | 7.32 | 8.96 | 16.21 |

A screenshot of a graph

Description automatically generated

Figure S11. The results of the location of the fault plane for each dataset. The rows from top to bottom represent datasets 1, 2, 4, and 5. The first row corresponds to the dataset when setting the range of on-fault aftershocks as 125 meters on each side from the final fit plane. The second row displays the results for a range of 2 km.

A graph of a diagram

Description automatically generated with medium confidence

Figure S12. Fault planes were obtained from Datasets 1, 2, 4, and 5.

Despite the different length-width ratios of fault planes from each dataset, the rupture area remains the same due to scaling from the mainshock magnitude. The length-width ratios differ between 250 m on-fault aftershocks and 4 km on-fault aftershocks within the same dataset. This difference arises because the wider range of on-fault aftershocks includes more events in the fault plane identification, potentially altering the location of the plane with the maximum cumulative energy released from the aftershock sequences. Despite these varying ratios, the strike of the planes is predominantly North-South (Table S4), aligning with the location of the most clustering aftershocks (Figure S4). The dip of the planes is nearly vertical. The rupture depth corresponds with the depth distribution of aftershock (Figure S13), encompassing the region where the most aftershock energy is concentrated.

The minimum rupture depth of the fault plane ranges from 7.6 to 9.1 km, which is consistent with field investigations (La Greca & Quigley, 2021; La Greca et al., 2022) and previously published fault planes. The Woods Point earthquake fault plane is identified as a blind fault. Additionally, all fault planes intersect the mainshock hypocenter, a result of the weighted method applied. The central positioning of the mainshock within the fault planes suggests a bilateral rupture, which aligns with the findings of Quigley et al. (2021). The seismic moment (MO) scaled from the mainshock magnitude (MW 5.9) is 7.94\*1024 dynes, and the corresponding rupture area is 44.67 KM2. Based on Equation S11, the average displacement of the fault ruptured during the mainshock is calculated to be 0.59 m.

A graph of energy and frequency

Description automatically generated

Figure S13. The energy released from near-focus aftershock distribution in depth. The bin length is 0.5 km. The upper figure shows the energy released distribution, with the majority of energy being intensively released between 7.5 km and 16.5 km. The bottom figure shows the frequency of aftershocks in depth, with the majority of aftershocks occurring between 8.5 km and 17.5 km. Dataset 5 is used for these figures.

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