# A Model for Visual Assessment of Fault Plane Solutions and Active Tectonics Analysis Using the Global Centroid Moment Tensor Catalog

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## Abstract

In this study, individual fault plane solutions are developed using various methods to improve the understanding of active tectonics on a regional scale. The comparative analysis of a focal mechanism solution (FMS) has not elicited the attention of researchers. Therefore, this study aims 1) to visually analyze the fault plane solution for 20 local faults that are responsible for all the earthquakes that occurred using visualization techniques such as; fault parameters, the linked Bingham method, the ad hoc pressure (P) axis and tension (T) axis method, and the moment tensor method; 2) to identify the best method for FMS; and 3) to understand the active tectonics of a fault population. A comparative analysis of the models is systematically documented to improve the understanding of the methods. An analysis of the overall fault mechanism is conducted for the analytic determination of fault movement using fault population data from the Global Centroid Moment Tensor catalog. The approach used in this work is a newly designed method for analyzing the reliability of various techniques for fault mechanism and overall fault movement research. Findings show that for the fault mechanism analysis, the P and T axes method and the moment tensor method are better than the fault plane solution from the fault parameters and the linked Bingham method based on the input parameters, output information, model outfit, and accuracy. The moment tensor method is one of the best approaches for analyzing fault mechanism because the errors in the nine components used as input data for the modeling are negligible. Meanwhile, the P and T axes method is one of the best techniques for the overall analysis of fault movement. P and T dihedral analysis using Kamb contouring is modeled. It indicates that the overall mechanisms of compression and dilation are features at the NW–SE and E–W directions, respectively. This comprehensive and consistent analysis of the fault mechanism provides an overview of the seismotectonic settings in Sabah, Malaysia.

**Keywords:** Fault mechanism; Active tectonics; GIS; Dihedral analysis; GCMT

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## 1. Introduction

Malaysia exhibits relatively low seismicity compared with other places, such as Sumatra, Japan, Chile, California, and the Himalayan region. For the state of Sabah, however, earthquakes of local origin have been recorded to occur historically. From 1923 to 2007, Sabah experienced 65 earthquakes, with magnitudes ranging from 3.3 to 6.5 based on the Richter magnitude scale. These earthquakes were produced by several inland and surrounding local faults.

Research on earthquakes in Sabah, Malaysia has been effectively documented through numerous seismic analyses. Several comprehensive analyses have been conducted to understand seismodynamics, fault characteristics, and fault types (Byrkjeland et al. 2000; Hicks et al. 2000). Fault reactivation, long-term stress, and fault weakness may create a potential environment for the repeated occurrence of earthquakes (Hicks et al. 2000). The focal mechanisms of small to medium earthquakes can be used to infer the structure and kinematics of faults at depth and to constrain the crustal stress field in which the earthquakes occur. It is therefore important to determine the mechanisms for small events as accurately as possible. These mechanisms are most often found using P-wave first-motion polarities recorded at local seismic stations. Each observed P arrival is mapped to the orientation at which the ray left the focal sphere, and nodal planes are fit to the set of observations (e.g. Hardebeck and Shearer 2002). A number of studies have also applied for S/P amplitude ratios using P wave first motion polarity (e.g. Kisslinger 1980; Kisslinger et al. 1981; Julian and Foulger 1996) or absolute P and S amplitudes (e.g., Ebel and Bonjer 1990; Ro¨gnvaldsson and Slunga 1993; Hardebeck and Shearer 2003**;** Nakamura et al. 2009) to determine the focal mechanisms. At least 10 waveform records from seismometers are required to obtain a well-modeled focal mechanism analysis. The fault plane mechanism has also been investigated using fault data and modeled through stereonet, which enables a relevant analysis of the focal mechanism. The complete analysis and characterization of the focal mechanism of an earthquake can provide information, including the depth of the source, the energy of an earthquake, location of epicenter and the orientation of nine moment tensor components (Cronin 2010). Fault plane solution can be implemented through various well-developed techniques by using such information. The modeling of the fault plane mechanism in the form of a beach ball diagram is a serious issue, and modeling accuracy is important to understand the entire mechanism. However, faults pose a major issue in this modeling because the surface of faults is not simple and may not be a plane (Dehls and Olesen 1997; Dehls and Olesen 1998; Dehls and Olesen 2000). Important information, such as the fault plane orientation, slip direction, and fault type, can be collected by analyzing and interpreting the graphic design of a beach ball diagram (Hicks et al. 2000). Such information will help seismologists and geologists understand the dynamic nature of faults and seismotectonic characteristics. The data of three types of mechanism can be recorded and distinguished from the focal mechanism analysis in the database. A single focal mechanism, a formal inversion focal mechanism, and an average focal mechanism can be analyzed to improve the understanding of the fault plane. Several methods, such as the first motion of P-waves, the polarization and amplitude of S-waves (Khattri 1973), the analysis of P/S amplitude ratios (Kisslinger 1981), and moment tensor inversion, are used to determine focal mechanism solution (FMS) (Stein and Wysession 2003) The pressure (P) axis, null (B) axes, and tension (T) axis require careful treatment when being averaged in the case of the average focal mechanism because of their circular distribution; moreover, disregarding the plunge when averaging trends is problematic (Lund and Townend 2007). The logical difference between moment tensor and stress tensor is not considered by the average focal mechanism. Many case studies on FMS using various methods have been documented over the last decade

(Khattri 1973; Kisslinger et al. 1981; Michael 1987; Rivera and Cisternas 1990; Sbar et al. 1972).

The study area is characterized by complicated structural features, such as large local faults and lineaments. Bailey et al., (2010) presented a statistical analysis of focal mechanism data generated from first motion polarities. They presented the solution based on P and T axis distribution and moment tensor through beach ball diagram. Marrett and Allmendinger (1990) presented numerical and graphical techniques to perform qualitative and quantitative analysis. They used Bingham statistics, moment tensor, P and T axes format and graphical contouring to project the average incremental strain. They also described the moment tensor summation and performed the numerical analysis that yields about the principal axes orientations, rotation and magnitude information. However, we have not performed the first p wave inversion for focal mechanism analysis in this work. In general, we have used the fault plane characteristics to project the focal mechanism for visual analysis of all local faults with good quality solutions in Sabah. Therefore, we design a model to determine the best method for best visualization of the fault mechanism solution by considering good-quality input raw data, fitted methodology, and error minimization, which can increase model quality and accuracy. In addition, the collected data are sufficient for reliable FMS, which enables systematic modeling. Before conducting seismic assessment studies, the kinematic history of fault movements and the structural intersection of faults that lead to the isoseismic elongation of the study area must be understood by analyzing the fault mechanism using the aforementioned model, which will improve the understanding of the active tectonic setting.

The problem states that no suitable comprehensive model is available for selecting the best method for modeling, visually analyzing the fault plane solution, understanding the history of fault movements and active tectonics. However, specific problems are the understanding of fault zone heterogeneity at several seismogenic depths and a visual interpretation of the focal mechanism. Therefore, use of graphical representation of fault slip data to minimize complexity problems, and issue associated to discover patterns of data, recognize trends, and finally, hypotheses development are needed. Another problem is to understand how the geometric criteria could distinguish the kinematic heterogeneities generated by multiple deformations, which could be done by integrating the dynamic and kinematic fault-slip results. The chosen study area for the focal mechanism solution was Sabah state in Malaysia because of its unique geography and its proximity to the  pacific ring of fire . This study tests four visualization techniques for modeling the fault mechanism solution. Therefore, a comparative assessment of methods is necessary to understand the quality, accuracy, strength, and limitations of methods based on the visualization approach. All the methods depend on their techniques and input parameters to create well-designed models. This study aims to develop a comprehensive systematic model to identify the most suitable method for visually analyzing the fault plane solutions and overall analyses of fault population in Sabah, Malaysia.

## 2. Study area

The state of Sabah in Malaysia is a highly hazardous region in terms of earthquakes not because of its tectonic boundaries but due to its large local faults. However, the subduction plate boundary is far from Sabah, and high-magnitude earthquakes only affect the state. The non-uniformity of seismicity clearly indicates the issue in a complicated seismotectonic region, such as Sabah. Most earthquakes are local and concentrated in the Central North Zone, the Labuk Bay Sandakan Zone, and the Dent–Semporna Peninsular Zone (Alexander et al. 2006; Cheng 2016), which can potentially induce highly destructive seismicity. An overall estimation of earthquake hazard has been conducted in Sabah by several authors using the catalog of large-magnitude earthquakes (Ekstr¨om et al. 2005; Mendoza et al. 1994). Most local earthquakes occur due to fault movements. However, the tectonic behavior of all inland

and surrounding faults in Sabah, which are mostly responsible for these earthquakes, must be understood. Accordingly, we selected the latitude of −4 to 7.5 and the longitude of −115 to 120 for fault mechanism analysis in Sabah.

**Figure 1. Study area in Sabah, Malaysia for fault analysis.**

## 2. Materials and methods

### 3.1. Data

The required data were collected from the Global Centroid Moment Tensor (GCMT) based on fault locality, which can provide sufficient precision in beach ball and stereographic plotting. This area faces a higher risk than other parts of Malaysia. The data are collected from the GCMT catalog on the basis of the following criteria (Table 1). Data for the state of Sabah and its surrounding areas were collected. Four formats are available for inputting data into software; among these formats, Aki Richards' format and the P and T axes format are the most effective and are recommended by most seismologists (Begg and Grey 2002; Hicks et al. 2000). Lehocki et al. (2014) utilized the Aki-Richards approximation (Aki and Richards 1980) of the Zoeppritz equation (Zoeppritz 1919) for the seismic gathers inversion of calibrated PP and PS based on the recommendation by Jerez, 2003. Jerez (2004) used an iterative scheme for nonlinear algebraic equations to solve the project, by linearizing the issue. They mentioned that Aki-Richards approximation is the most efficient format to solve the unknown data. They tested the sensitivity of the format and the input and output errors by analyzing some modelling data. Therefore, we selected these formats for analysis and modeling. In addition to the data, several symbols, namely, N (normal), T (thrust), R (right lateral), and L (left lateral), were used for the sense of slip.

**Table 1. Search criteria for Sabah, Malaysia that enable GCMT data collection.**

The collected data are listed in Table 2. The data are presented in a complete pattern with all the parameters. A minimum of three data elements is generally required for modeling the fault plane solution: two for the orientation specification and one for slip direction (Cronin 2010). Nevertheless, we have more elements to construct an accurate fault plane solution diagram. The orientation of the interpreted fault after an earthquake and the slip vector are sufficient for the fault plane solution; however, other elements, such as striae trend and plunge and P and T axes information, can improve the accuracy of a model (Cronin et al. 2008). Many earthquakes originate from the double couple mechanism, whereas others originate from a highly complicated mechanism. However, a tectonic setting may be involved in a multiple fault system. Understanding the focal mechanism via the frictional slip is difficult. To solve this problem, additional data are required for the graphical modeling of the focal mechanism. Table 2 presents the data collected from the GCMT catalog for determining the fault plane solution in Sabah, Malaysia with good accuracy.

**Table 2. Data used for the fault plane solution.**

### 3.2. Methodology

Faultkin (version 7.5) is a geological software package for structural geological analysis. This software accepts only data in text format or direct entry via manual editing. The first step is to make a new dataset in a word file and then convert it to text format to be used in Faultkin. The most important aspect of this software is its capability to handle incomplete data in an appropriate manner. It can make assumptions on the basis of collected sub-datasets by conducting system calculations. In the current case, the data are complete. The plunge and slip of the faults are calculated using the P and T axes Method. The collected data from the GCMT catalog were used to analyze the fault plane solution. Understanding the collected data is crucial for the appropriate analysis and comparison of fault plane mechanism models. The relationship between fault plane movements and the tectonic setting is important. Therefore, the model developed in this study can provide a general understanding of the fault plane, HW (Hanging wall) slip direction, and tangent direction to the plane, movement plane, and kinetic axes by plotting all delineate in the stereo diagram. The data were used for the stereographic projection and analysis of fault characteristics. The nodal and fault planes are perpendicular to each other and are presented as huge circles in the stereographic diagram. Therefore, all the 20 fault planes were plotted along with the movement planes, slip direction, tangent direction, and kinetic axes.

Transformation from the moment tensor to the two fault planes is possible with several mathematical analyses. The eigenvectors (t, b, and p) of the moment tensor were obtained. The nine components are described below in matrix format. The moment tensor can determine the fault parameters, such as the strike, dip, and slip of a fault plane (Cronin 2010). Numerous methods for describing all the aforementioned information have been derived from focal mechanism analysis. The main decompose possibilities of a full moment tensor, are generally an isotropic, deviatoric moment tensor and into a mixed-mode pure shear tensor as well as a residual isotropic tensor. According to the different elementary sources, again the deviatoric component can possibly be decomposed. The most important thing to note is that there are specifically three unique focal mechanisms that can be represented in a diagram. However, the five mechanisms we described above can be recreated by modifying and relocating the orientation of unique mechanisms. For example, an explosion occurred at a specific location that can provide an isotropic tensor that exerts the radial forces same in every direction without any variation in the amplitude of the waves, however, the first motion must be radially outwards. Therefore, it creates an isotropic moment tensor with a first P wave amplitude which is positive. Another mode of moment tensor which is a deviatoric mechanism becomes tilted on its side and oppositely compressing. The other mode of moment tensor is because of pure shear cracks which are oriented ninety degrees and double couples**.** The method described below is the pure shear moment tensor and it is a good technique for fault mechanism analysis:

$$\begin{bmatrix} \boldsymbol{M}\mathbf{11} & \boldsymbol{M}\mathbf{12} & \boldsymbol{M}\mathbf{13} \\ \boldsymbol{M}\mathbf{21} & \boldsymbol{M}\mathbf{22} & \boldsymbol{M}\mathbf{23} \\ \boldsymbol{M}\mathbf{31} & \boldsymbol{M}\mathbf{32} & \boldsymbol{M}\mathbf{33} \end{bmatrix} = (\mathbf{t}\ \ \mathbf{b}\ \ \mathbf{p}) \begin{bmatrix} \boldsymbol{M}\mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & -\boldsymbol{M}\mathbf{0} \end{bmatrix} \quad (\mathbf{t}\ \ \mathbf{b}\ \ \mathbf{p})\mathbf{T}. \qquad \text{Eq. (1)}$$

Subsequently, the fault vector (n: normal vector of a fault plane, v: slip vector) was obtained from the eigenvectors (t, b, and p) using the following equations:

$$\boldsymbol{n} = ½\ (\boldsymbol{t} + \boldsymbol{p}), \boldsymbol{v} = ½\ (\boldsymbol{t} - \boldsymbol{p}), \qquad \text{Eq. (2)}$$

$$\boldsymbol{n} = ½\ (\boldsymbol{t} - \boldsymbol{p}), \boldsymbol{v} = ½\ (\boldsymbol{t} + \boldsymbol{p}). \qquad \text{Eq. (3)}$$

According to the study by Knopoff and Randall (1970) and Fitch el al. (1980), it is possible to decompose the moment tensor into different parts of isotropic part, a compensated linear vector dipole and a double couple. If we assume that $|\boldsymbol{m}_3^*| \geq |\boldsymbol{m}_2^*| \geq |\boldsymbol{m}_1^*|$ . The deviatoric moment tensor can be described as;

$$\overline{\boldsymbol{m_1}} = \boldsymbol{m_3^*}\begin{bmatrix} -\boldsymbol{F} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & (\boldsymbol{F}-\boldsymbol{1}) & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \qquad \text{Eq. (4)}$$

where F = $\boldsymbol{m_1^*}$ / $\boldsymbol{m_3^*}$ and (F-1) = $\boldsymbol{m_1^*}/\boldsymbol{m_3^*}$. It must be noted that; $\boldsymbol{0} \leq \boldsymbol{F} \leq \boldsymbol{0.5}$. From the deviatoric condition, F arises as; $\boldsymbol{m_1^*} + \boldsymbol{m_2^*} + \boldsymbol{m_3^*}$= 0. By representing the CLVD and double couple we can simply decompose as;

$$\overline{\boldsymbol{m_1}} = \boldsymbol{m_3^*}(\boldsymbol{1}-\boldsymbol{2F})\begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & -\boldsymbol{1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} + \boldsymbol{m_3^*F}\begin{bmatrix} -\boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & -\boldsymbol{1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{2} \end{bmatrix} \text{ Eq. (5)}$$

We assumed here that double couple and CLVD are produced by the principal stresses and the full decomposition can be represented as;

$$\boldsymbol{M} = \frac{\boldsymbol{1}}{\boldsymbol{3}}(\boldsymbol{m_1} + \boldsymbol{m_2} + \boldsymbol{m_3})\boldsymbol{I} + \boldsymbol{m_3^*}\ (\boldsymbol{1}-\boldsymbol{2F})(\boldsymbol{a_3a_3} - \boldsymbol{a_2a_2}) + \boldsymbol{m_3^*}\ \boldsymbol{F}(\boldsymbol{2a_3a_3} - \boldsymbol{a_2a_2} - \boldsymbol{a_1a_1}) \quad \text{Eq. (6)}$$

From the pure double couple model the seismic source deviation can be estimated by using the parameter as;

$\boldsymbol{\epsilon} = \left|\frac{\boldsymbol{m_{min}^*}}{\boldsymbol{m_{max}^*}}\right|$ where $\boldsymbol{m_{min}^*}$ is the smallest eigen value while $\boldsymbol{m_{max}^*}$ is the largest eigen value

Some other researchers (Giardini 1984) also investigated the variation of $\boldsymbol{\epsilon}$ with respect to spatial distribution of seismic events and the seismic moment.

Four different methods were used to model the fault plane solution. The methods that are generally used for fault mechanism solutions are the ad hoc P and T axes method, the moment tensor solution method, the fault plane solution from fault parameters, and the linked Bingham method. The ad hoc P and T axes method and the linked Bingham method were used in Faultkin to construct models with good accuracy. The fault plane solution from the fault parameters and the moment tensor method are modeled using ENVI software. Many methods have been developed to analyze the fault plane solution but the T and P axes method is used as the kinematic method for slip analysis. P and T dihedral analysis is performed to understand the orientation of stress axes for a population of faults of any kind. Moment tensor is a highly accurate method for analyzing the nine components derived from the focal mechanism analysis. Fault plane parameters are used for modeling, and the Bingham method is good for fault mechanism solutions. The overall mechanism of fault movement and P and T dihedral analysis are conducted to understand the tectonics in Sabah. The overall flowchart of the methodology is provided in Figure 2.

**Figure 2. Overall flowchart of the methodology.**

## 3. Results and discussion

The data were plotted in stereonet and it provides valuable information about fault tectonics. As shown clearly in the Figure 3, some faults intersect, whereas others are individual in nature. The intersection of faults leads to isoseismic elongation, which can create destructive earthquakes. This stereographic diagram is important for overall fault movement analysis (Cronin et al. 2008). All the results obtained from the study are presented using modeling software Faultkin and ENVI. The modeling of the fault mechanism solution derived from the linked Bingham method, ad hoc P and T axes method, and centroid moment tensor method is performed on the basis of the data collected using Faultkin, whereas the solution derived from the fault parameters only is modeled using ENVI.

**Figure 3. Stereographic plot of faults that represent the 20 major local faults and the details of the strike, dip, and slip movements of materials in the movement plane, and the P and T axes of faults in stereonet**.

### 4.1 Fault plane solution from fault parameters

Fault plane solution is derived from three fault parameters, namely, strike, dip, and slip. Models are presented by two auxiliary planes of fault and a nodal plane (Figure 4a). In general, these models are average fault plane mechanism. During an earthquake, material movement occurs via compression and extension (Cronin 2010). These models are sufficient to understand the fault plane mechanism after an earthquake. However, small-magnitude earthquakes cannot provide the correct slip information, which may change the model.

### 4.2. Linked Bingham method

Graphical contouring and Bingham statistics of the P and T axes for kinematically scale-invariant faults characterize the distributions and orientations of the principal axes of an average incremental strain (Begg and Grey 2002). Fault plane solution is analyzed using Faultkin version. 7.5, which was developed by R. W. Allmendinger, R. A. Marrett, and T. Cladouhos (Figure 4b). A total of 20 fault planes with subset data were used for the analysis. The linked Bingham axes, which lie in the movement plane and the cross section of the fault planes, were calculated using Faultkin. Then, the models were used to understand material movement. The axes and mechanism of fault movement derived from linked Bingham analysis must be understood. The linked Bingham statistics of the axes correspond to the directional maxima of the P and T axes of a fault population (Mardia 1972). The unweighted moment tensor is equivalent to the linked Bingham axes, where all the 20 faults were equally weighted. The Bingham statistical analysis of fault population does not consider the magnitude of deformation. Therefore, the linked Bingham method is one of the best methods for fault plane solution, which can provide information regarding material movement.

### 4.3. P and T axes method

The P and T axes represent the pressure and tension, respectively. They can be constructed by bisecting the nodal planes of a designed model of a fault plane solution that lie at 45° to the fault and nodal planes. These axes are kinematic in nature, and they represent the principal axes of a fault (Begg and Grey 2002). Therefore, the graphical representation of the P and T axes for a fault population is important in kinematic analysis. The sense of slip of a designed model distinguishes between the two axes. The kinematic axes of faults cannot be interpreted from field survey. Only the observed data can be converted to a fault plane solution. The kinematic axes of a fault population can be represented by performing various geometric tests. In the P and T axes analysis method, contouring all P and T axes are realized using the Kamb contouring method (Kamb 1959). A potential problem in Kamb contouring is that the P and T axes are distinct rather than linked to each other, which is unimportant in our modeling. At present, the P and T axes can be easily defined by seismologists on the basis of their nature. Therefore, the models we designed for the fault plane solution using the P and T axes method in Faultkin exhibit good accuracy and modeling outlook (Figure 4c).

**Figure 4. a) Fault plane solution derived from fault parameters, b) Fault plane solution derived from the linked Bingham method, c) Fault plane solution derived from the ad hoc P and T axes method.**

### 4.4. Moment tensor solution

Seismic moment tensor is a second-order symmetric tensor that consists of nine components, which are equivalent to body forces (Cronin 2010). Moment tensor is symmetric in nature, thereby ensuring the conservation of angular momentum (Jost and Hermann 1989). Moment tensor can be calculated from the waveform data of body and surface waves. After moment tensor is calculated, the focal mechanism of earthquakes can be calculated via inversion. Therefore, we present the FMS of the 20 faults in Sabah derived using moment tensor (Figure 5).

**Figure 5. Fault plane solution derived from the centroid moment tensor method.**

Moment tensor was calculated using ENVI software, converted to nine components, and compared with moment tensor data in GCMT, thereby increasing the accuracy of the models. In general, the quality of fault plane solutions derived using any method is dependent on the collected data, knowledge about Earth’s structure, and modeling criteria. Insufficient data and knowledge may lead to an erroneous focal mechanism. Strain axes, which are equivalent to principal axes, can be derived from the seismic moment tensor. Seismic moment tensor in GCMT includes other information rather than moment tensor components. Details regarding moment tensor can be found in (Jost and Hermann 1989; Stein and Wysession 2003) or standard seismology books.

## 5. Comparison of methods

All the visualization methods are highly suitable with respect to their algorithm and input data. We can understand their differences by comparing the four methods used in modeling of fault plane solution. The quality of fault plane solutions depends on the quality of raw data, fitted algorithm, and procedures for error minimization. The requirement of a suitable method that considers methodological limitations and accuracy is important to achieve a reliable fault plane solution (Dahm and Krüger 1999). Therefore, we comparatively discuss the four methods used to prepare the fault plane solutions in Table 3. The current resolution and quality of the models are improved compared with those in earlier research. All the models presented by the methods emphasize the P and T components with material movement. Therefore, the models that resulted from the moment tensor method have a different outlook compared with other models.

**Table 3. Comparative assessment of visualization results used in fault plane solution modelling.**

**Figure 6. Tectonics of Sabah represented using the rose diagram.**

**Figure 7. Total P and T axes with Kamb contouring and their dihedrals.**

### 5.1. Overall mechanism and tectonics analysis

In general, faults are used as dynamic indicators by using stress inversion (Angelier 1984; Etchecopar et al. 1981; Gephart and Forsyth 1984; Michael 1984; Rivera and Cisternas 1990). Figure 8 provides information about faults, lineaments, lithology, and earthquakes from 1976 to 2017. The strikes of all the 20 faults are analyzed and plotted in a rose diagram (Figure 6). The rose diagram of strikes and dip direction for all the faults clearly tends toward the NE–SW and NW–SE directions, respectively. In addition, most faults are directed toward the NE–SW direction, whereas extremely few faults are directed toward the NW–SE direction. The highest dip angle of 79° can be found toward the N–E direction, whereas the lowest one is found toward the S–E direction. A high dip of faults is influenced by seismic waves. If faults intersect, then they can influence one another, thereby leading to destructive earthquakes. However, a gap of angles 340° to 40° exists, where no dip direction of faults can be found. The P and T axes observed from the fault slip analysis using various sub-datasets of 20 faults can be directly equated with compressive stress. In Figure 9, the P and T axes are plotted using stereonet. Contour lines are developed for the P and T axes and plotted in stereonet to improve understanding using Kamb contouring (Figure 7). Moreover, contour lines are developed based on certain criteria, such as contour interval (C.I)-2 sigma, significance level (S. level)-3 sigma, and grid spacing (G. spacing)-20. For all the 20 faults, P and T dihedral analyses are modeled with an expected number of 6. Therefore, the entire net is divided into various parts using different numbers ranging from 6 to 15. These numbers can help in the subsequent step for modeling the P and T dihedral analysis of a fault array.

All the earthquakes happened in this area, if we categorized into two sections of low magnitude and medium magnitude earthquakes then we can understand the fault movement is different for different earthquakes in the same fault. For a different earthquake, by analysing the strike, dip and dip direction, one could recognize the variation.

## 5.2. Dihedral analysis

Figure 8a shows the stereonet diagram with a population of 20 faults, with the P and T components modeled using Kamb contouring. Faults with a huge circle and their conjugate planes are also shown. According to MacKenzie (1969), some places are characterized by pre-existing fractures; therefore, the principal stress axes and the P and T axes may vary. However, the largest principal stress may be found anywhere in the P quadrant; similarly, the least stress axis may virtually occur in the T quadrant. This model shows compression and extension in a highly complicated structure. In the next step, smooth analysis is conducted to reduce the complexity of the model. The smooth analysis of the predeveloped model is modified into a well-outperformed model with accuracy. Moreover, the smoothed model represents the compression and extension toward the NW–SE direction in the stereonet. Figure 8b presents P and T dihedrals through the equal area stereo diagram. The region within the T quadrant of all the 20 faults is shaded in red, whereas the P quadrant is shaded in white. Therefore, the shaded contour in the T quadrant that results from the fault population with numbers 13, 14, and 15 is the T dihedral found at the NW–SE direction of the stereonet. In the P quadrant, the P dihedral is found with the contours of numbers 13 and 14 at the E–W direction of the stereonet. Lisle (1987) demonstrated that dihedral analysis can be improved by considering the stress ratio (R), which affects the analysis. This information can help understand the overall material movement due to an active fault population. Consequently, it can be used as a basis for understanding active tectonic setting. The details of the P and T dihedral analysis are found in (Angelier 1984; Lisle 1987; McKenzie 1969).

**Figure 8. (a) P and T areas in stereonet. (b) Results of P and T dihedral analysis.**

### 5.3. Multiple deformation

Due to multiple deformations, fault-slip occurs and the kinematics indicate that the deformation is heterogeneous in nature. When two deformations occur internally, which are distinct kinematics but coherent, affect the specific rock continuously. A special type of anisotropy reactivation resulted due to superposed deformations in which historical active faults again reactivated, producing a second set of striae that was presented in (Figure 9). Therefore, individual faults in the study area show that the slip occurred in at least two or more appropriate directions and the most important point is a single set of faults characterized by different slip directions. Therefore, the kinematics of fault-slip for the specific deformation may be incompatible with the deformation of another kinematics. Moreover, independent proof of multiple deformations comprises of standardized cross-cutting connections of two average straie. Therefore, all the average straie are falling over the average fault plane of the recent five earthquakes occurred in the study area. Therefore, the results show that there are multiple deformations because of reactivation of faults. These faults may produce more earthquakes in the future because of reactivation

**Figure 9. Shows the multiple deformation of seismically active study area.**

## 6. Validation

All earthquakes that occurred in Sabah were caused by 20 local major faults. To validate the derived fault plane solution from various methods, the details of the data and the overview of the models can be found in the GCMT catalog (http://www.globalcmt.org/CMTsearch.html). A comparative analysis of the P and T axes from three methods was performed. However, the trend and plunge of the P and T axes derived from the linked Bingham and fault plane solutions are the same. However, the trend and plunge of the P and T axes derived from moment tensor slightly differ, i.e., 359.9, 090.4 and 16.36, 01.57, respectively (Table 4). The P and T axes derived from all three methods are highlighted in Tables 4, 5, and 6.

**Table 4. P and T axes derived from the linked Bingham analysis.**

Moreover, these methods provide additional information about eigenvalues, double couple %, CLVD (compensated linear-vector dipole) %, and fault parameters, including slip sense and rake. Comparing or verifying results with observations is important. Therefore, we verify the obtained models with the GCMT project (http://www.globalcmt.org/). The overall movement of faults in a fault population that results from the observation using the same methods is correct and accurate.

**Table 5. P and T axes derived from the fault plane solution.**

**Table 6. P and T axes derived from moment tensor.**

## 7. Conclusion

The modeling of a fault plane solution and the kinematic analysis of fault slip data using various methods summarize the qualitative and quantitative results for understanding tectonics. The accuracy of models can be enhanced through appropriate analysis, complete data, and by improving data quality. Therefore, graphical methods are suitable for an effective analysis of the fault mechanism. Moreover, certain assumptions must be made for fault population analysis, which can be outperformed by using Faultkin version 7.5 software.

Graphical methods are helpful in kinematic heterogeneity analysis. Many comprehensive studies have been performed in Sabah with regard to active tectonics. Therefore, this study will help in understanding the focal mechanism of fault movements and in identifying the best method for modeling fault plane solution. This work confirmed that these visualization methods, as well as the fault plane solutions, can be used in studies aiming at seismicity and modifying the visualization results. Following the results of the fault plane solutions of tectonic earthquakes from Sabah, the significant analysis of full MT should be the part of the discrimination workflow, however, it cannot be considered as the primary and only analysis for such discrimination. Isotopic as well as the residual isotopic form of analysis need to apply for the visualization analysis. This work is directed towards the future seismicity analysis through visualization techniques to improve the understanding of tectonics.

All the methods are applied to different environments using various data. The following conclusions are drawn from this study. Determining which nodal plane is the fault plane is difficult, and the fault plane can be identified by analyzing higher degree moment tensor. Therefore, fault planes can be identified by analyzing aftershock distribution and through field surveys. The comparative analysis of the four methods clearly describes the best method for modeling fault plane solutions, which depends on the percentage of errors in data quality.

If we regard all the 20 faults in the study area as one, then we can understand the overall movement of the fault array. The overall fault plane mechanism shows that the behavior of a fault is similar to that of a strike–slip thrust fault. The movement behavior of nodal planes is insufficient to identify the fault plane. Fault plane solution with Kamb contouring shows overall compression and extension. The particle movement tends to be toward the northern region of the study area. The northern and southern parts of the stereonet are compressed for the study area. However, the smooth analysis result shows the NW and SE directions. P and T dihedral analysis presents fully compressed and extended areas of the entire region. The entire area is divided into different numbers based on compression and extension. The highest numbers of 13 and 14 exhibit contouring, which indicates that the contoured part is the commonly compressed and extended part of all the faults. Minimal deformation is observed in the T dihedral analysis of the SE region because material movement is toward the NE region.

**Funding:** This research is supported by Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS), UTS grant numbers 321740.2232335, 323930, and 321740.2232357.

**Conflicts of Interest:** “The authors declare no conflict of interest’’.

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## LIST OF TABLES AND FIGURES

Figure 10. (a) P and T areas in stereonet. (b) Results of P and T dihedral analysis.

Figure 11. Shows the multiple deformation of seismically active study area.

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