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Full Paper

Magnetotelluric survey for active fault mapping: Lahad Datu case study

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Abstract: Sabah in Malaysia is severely affected by tectonically active neighbouring plates that are under stress due to compressional forces dominantly in NW-SE direction. The compression causes ground breakage via faults, active and non-active. The active faults pose a threat to human and environment at large; thus, information on the matter is a necessity. This study aims to locate and assess the active fault at Lahad Datu, which is one of the seismically active locations in Sabah by using magnetotelluric method. The result shows the existence of an active fault with low resistivity values (<5 Ωm) in the region. The identified NE-SW thrust fault is correlated with existing lineament data. The research provides valuable information for hazard planning for the locality.

Keywords: magnetotellurics, active fault, resistivity, Sabah, Malaysia

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INTRODUCTION

A fault is a planar fracture resulting from compressional or tensional force in the earth subsurface, which builds up from smaller fault segments and causes displacement of brittle rock bodies [1]. Active faults commonly generate systematic and continuous displacement of the rock bodies over an extensive area and are clear indications that the region is currently enduring stress. Active fault zones are the common source locations for the occurrence of earthquake sequences [2].

Maejo Int. J. Sci. Technol. **2022**, *16*(01), 40-50

This study took place at Lahad Datu in Sabah, Malaysia as earthquake records in the area have spiked since 1900, which signifies Lahad Datu's close association with active faults [3, 4]. Destructive earthquakes are rare in onshore Sabah as the epicentres are typically of shallow depths with moderate magnitudes of less than M_W 5.9 [5]. The July 1976 Lahad Datu earthquake was one of the most disastrous earthquakes in Sabah with a magnitude of 6.2, which damaged properties and infrastructures near the epicentre [6-8]. This was followed by nine more earthquakes up to 2012 [9]. Given the consecutive earthquakes occurring in the area, monitoring fault activities in this area is important in order to track their pattern.

Previous mapping of active faults in Lahad Datu was executed using remote sensing to demonstrate the existence of active faults in the area [10]. Geological evidence of thrust and strike-slip faults in the area was also observed [11]. However, both activities only considered features observed on the ground surface. Therefore, these findings need to be validated by ground studies. With little data available, especially on the subsurface, the fault system in the area is barely understood. Studies of Lahad Datu fault system are sparse with no geophysical information to map the fault system. This lack of knowledge triggers the idea to conduct this study.

With the knowledge of the existence of active faults in Sabah, it is vital to ascertain seismic hazards for the area in order to equip effective management strategies in the event of potential disastrous earthquake events. In light of this issue, this study focuses on Lahad Datu in delineating the faults in accordance with past seismic activity records in the area. This research employs magnetotelluric (MT) method to locate the potential active faults by conducting subsurface mapping at Lahad Datu.

REGIONAL GEOLOGY

Lahad Datu is located on the Sunda plate, a tectonically active plate that is surrounded by three other seismically active plates: Eurasian, Indian-Australian and Philippine Sea plates [12, 13]. The Eurasian plate is moving at a rate of 4 cm per year in the south-east direction while the Indian-Australian plate is moving almost twice as fast towards the north. Meanwhile, the Philippine plate moves 10 cm annually in the north-west direction. Interestingly, all of them are squeezing Sabah where the interactions between the tectonic plates generate several subduction zones and strike slip faults as shown in Figure 1 [11].

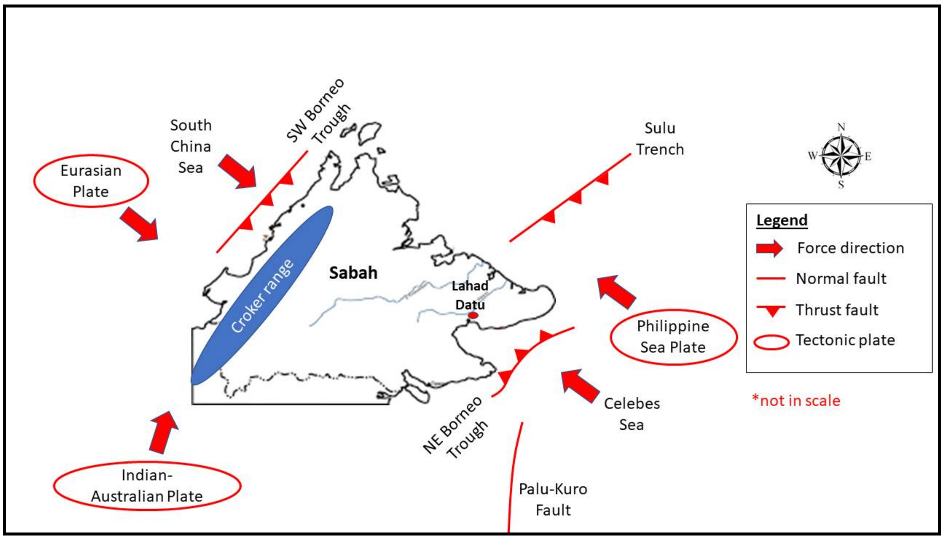

Figure 1. Simple schematic diagram illustrating the collective tectonic forces towards Sabah [11]

With its proximity to the Eurasian-Philippine plate boundaries (±1000 km), Sabah is most affected by two known active belts–Sulu Trench subduction and Palu-Koro Fault–which are nearest to Sabah. The boundary of the Sulu Trench subduction zone in Philippines extends towards Sabah, leading to the development of several NE-SW trending faults across Sabah. Concurrently, the active Palu-Kuro Fault in Sulawesi is also moving along NE Sabah coast, which is close to Tawau, Semporna and Lahad Datu [11]. Other forces that are exerting stress onto Sabah are the Southern China continental rift and Celebes Sea oceanic crust subduction from the north-west direction and south-east direction respectively, which has occurred since the Late Tertiary. Consequently, Sabah is sandwiched between the two continental bodies under NW-SE compressional forces. The compression is clearly manifested by the Croker Range [14]. Another major source that contributes to Sabah's fault system is Kinabalu pluton. Since its emplacement during early Late Miocene, the interaction between the pluton and the surrounding ambient crustal temperature has led to the pluton's rapid cooling, subsequently causing an enormous uplifting process in Sabah at the rate of 7 mm annually until Early Pliocene [15]. This further accentuates the complexity of active fault distribution throughout Sabah. Figure 2 shows a lineaments map and earthquake occurrences in Lahad Datu locality for the past years.

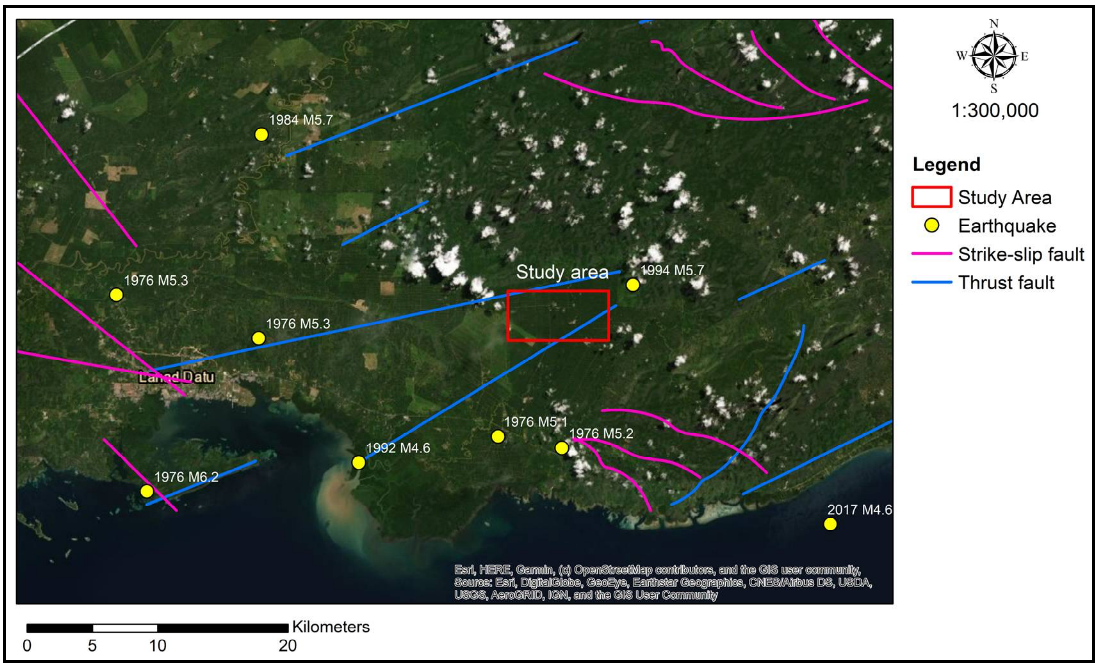

Figure 2. Lineaments map with earthquake locations for the past years (modified from Tongkul [11]). Earthquake data are obtained from US Geological Society [16].

From numerous tectonic events since the early Tertiary that has been studied thus far, it is apparent that Sabah, including Lahad Datu, has a diverse geological feature [17]. Normal continental crustal rocks were obducted and overlaid by the ophiolite complex during the Pre-Cenozoic and served as the base for sedimentary succession [18]. The Tabin region, which is located in the northern part of the study area, was a part of the volcanic arc during the early Miocene (22 Ma). Since then, the volcanic arc has gradually submerged into the Sulu Sea in the east while simultaneously transporting pyroclastics and sediments onto the study area [19]. The progressive deformation also caused migration of sediments from central Sabah to induce a *melange* formation in the Tabin area as shown in Figure 3 [20]. The size of the sediments ranges from argillaceous to arenaceous rocks and they also contain calcareous beds on occasion [21].

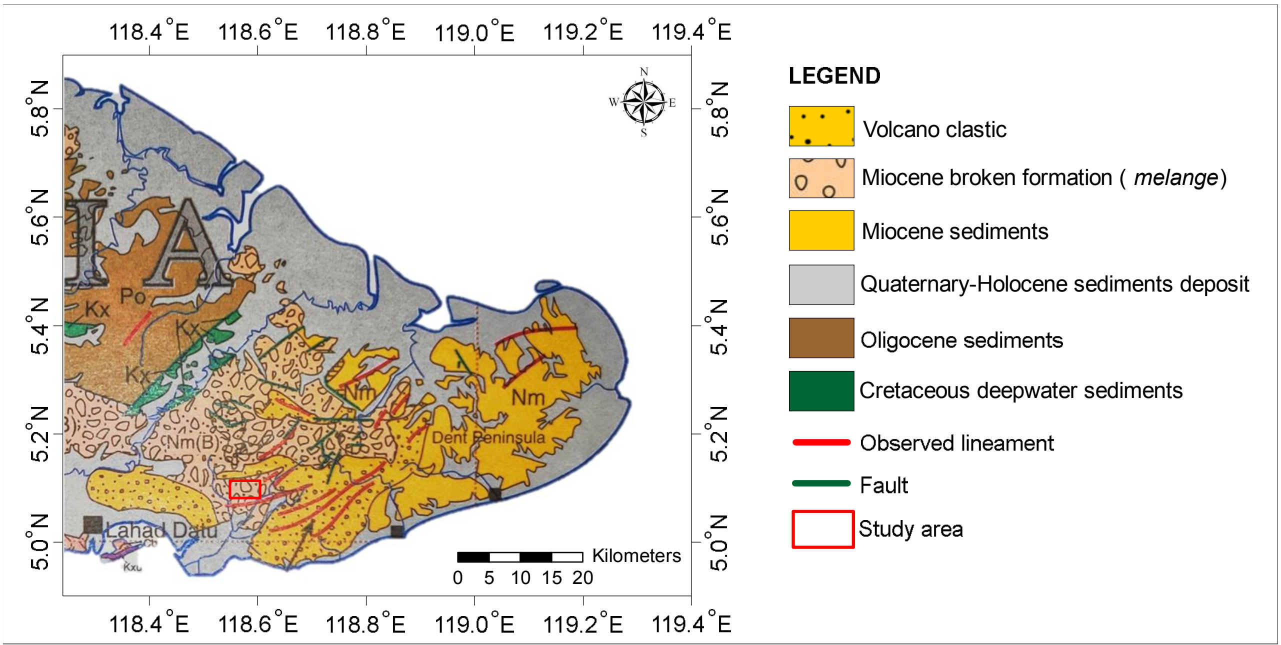

Figure 3. Geological map of Lahad Datu area [22]

MATERIALS AND METHODS

The study took place at Silabukan, Lahad Datu, which is situated at about 30 km to the east of Lahad Datu town and 10 km from the nearest shoreline in the south. The site is covered with palm oil plantations and is bounded by Tabin Wildlife Reserve in the north. From on-site observation, the study area has gradual elevation changes (25-35 m above mean sea level) due to hill stripping for plantation purpose. Several linear features can be observed in the vicinity that suggest fault trends in two dominant directions: NW-SE and NE-SW. The existence of the NW-SE faults is manifested by fault scarps, mud volcanoes and hot springs while the evidence for NE-SW faults can be seen in the splitting of tree trunks, semi-active mud volcanoes and road damages [11]. One of the well-known mud volcanoes in Sabah is Lipad mud volcano, which is located 15 km in the north-west direction from the study area [23, 24].

The MT method is a widely applied technique for measuring the electrical conductivity and portraying the structure of the Earth [25]. This passive geophysical method utilises naturally occurring electric and magnetic fields to investigate regions of interest beneath the Earth surface from tens of metre down to the upper mantle with an approximate 410-km depth [26, 27]. These attributes establish it as the most preferable and highly effective method in fault studies [28-31].

Figure 4 shows the location of the study area and MT stations in Silabukan, Lahad Datu. The north-south (NS) and west-east (WE) two-dimensional (2D) profiles were designed perpendicular to each other to detect the fault and determine its orientation. Each profile consists of five MT stations with a spacing of 800-1000 m between the stations. The MT data were collected using KMS technology system that requires electrodes to cover the electric field in the x- and y- directions (Ex and Ey) as geomagnetic north-south and east-west respectively. Two pairs of non-polarised copper - copper sulphate electrodes were planted directly into the soil to secure good ground electrolytic conduction with low impedance [32, 33]. The separation between the electrode pairs was 100 m, which is commonly used [34].

Meanwhile, magnetic coils were used to detect magnetic field fluctuations in the x-, y- and z-directions (Hx, Hy and Hz) where they were orientated to the north and east and vertically downward respectively [35]. The coils were buried 2 feet in the ground in the respective directions of the axis to minimise environmental noises. The induction coils are highly sensitive to the time-varying magnetic field in the axis direction because they are made up of tightly packed coils wound around a highly magnetic-permeable core. All electrode and coil units were connected to an automated computer system at the centre to collect the data simultaneously. This passive method uses natural electromagnetic signal with a frequency range of 0.0001 - 1000 Hz.

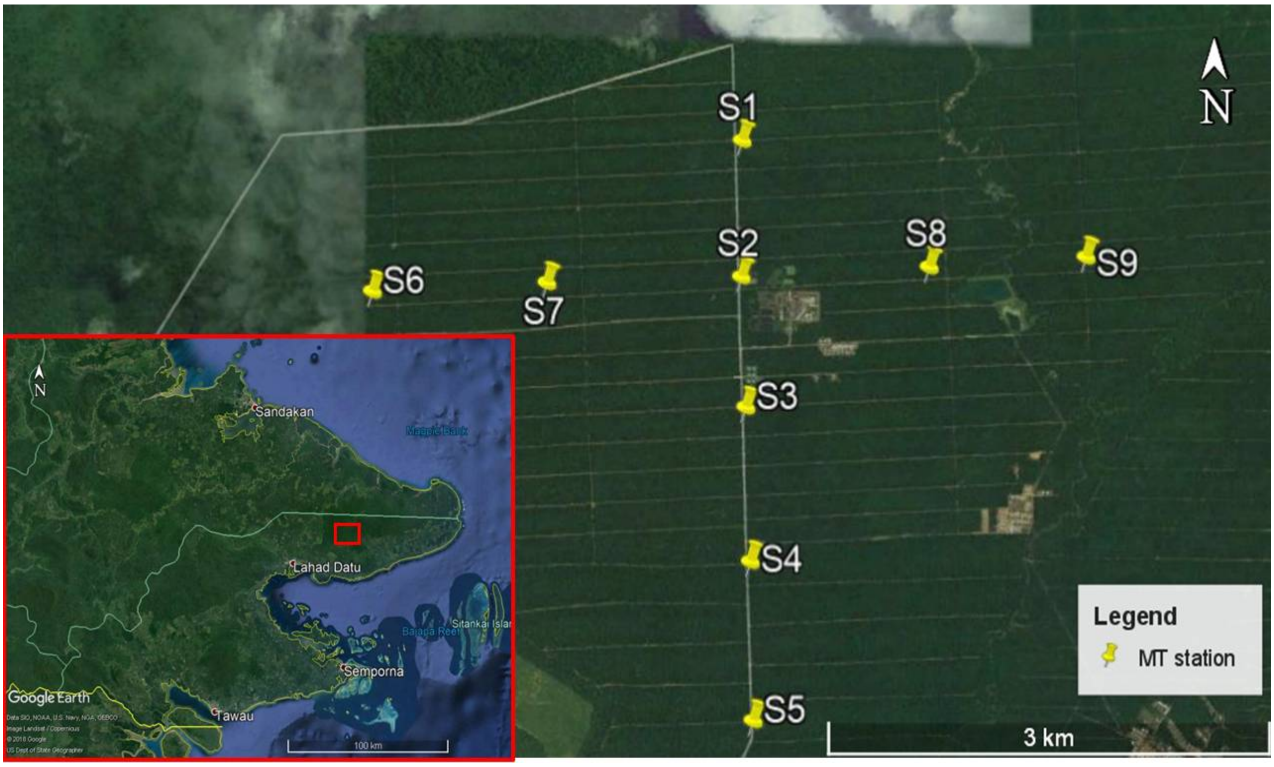

Figure 4. Location of Lahad Datu and MT stations [36]

Figure 5 displays the MT processing steps for obtaining the final 2D resistivity profile. The data were processed using basic MT processing software by starting with dividing the binary file of long-period data into smaller segments prior to applying Fourier transformation to the time-series data to resolve them into their constituent coefficients. Then the impedance tensor and variance were calculated from coherent electric field (E) and magnetic field (H) measured from the field. Robust regression method was executed to reduce the influence of outliers, thus improving impedance estimates. The MT data were plotted in resistivity and phase graphs as functions of logarithmic period [37].

Zond2DMT software was used for data inversion to minimise misfit between observed data and calculated synthetic data. Therefore, a more accurate result is obtained. Data smoothing was employed to avoid extreme contrast between adjacent cells. The output of the inversion is a 2D resistivity profile that consists of apparent resistivity values with respect to depth and distance.

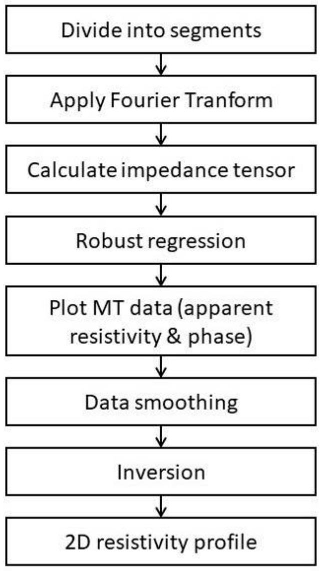

Figure 5. MT processing steps for obtaining 2D resistivity profile

RESULTS AND DISCUSSION

The inverted resistivity profiles are presented in Figure 6, where the NS and WE profiles cover up to 9 km in depth. The subsurface has resistivity distribution of 0.4 - 500 Ωm, suggesting a variety in geological formation which is divided into two major layers. The top layer has a thickness of about 1.5 km and is interpreted as sedimentary formation on account of moderate resistivity values observed in the region. The result is in accordance with the geological mapping of Sabah, which classifies the area as Neogene sedimentary formation of arenaceous and argillaceous rocks, coal and calcareous beds [20, 38]. In addition, the presence of numerous faults in the area contributes to low resistivity values obtained. A deeper layer is reachable to a maximum depth of 9 km. A very conductive zone (less than 5 Ωm) is observed in the NS profile and is located between highly resistive bodies at 2-5 km distance. This clear-cut structural feature is a good indicator of a deep fault, which extends sub-diagonally. The low-resistivity values of the fault are caused by the existence of tectonic fluid that resides within the fault [39]. The feature strongly suggests that the fault in the profile is of an active type as numerous seismic active regions are known to have such seismicity-resistivity relationship [40-42].

To determine the existing deep fault orientation in the locality, the result from the WE profile is crucial. A fault was identified in the WE profile at a distance of 4-6 km, which could be the continuity of the fault from the NS profile on account of the similarity in their physical properties such as resistivity values, pattern and dipping angles. Hence a conclusion can be drawn from this feature that an NE-SW orientated deep fault exists in the study area and is dipping towards the SE direction (Figure 7). This orientation agrees with previous geological and lineaments mapping in the surrounding locality [11], thus confirming the result obtained through the MT method. The fault could be associated with an earthquake-induced zone as shallow earthquakes are closely related to vertical conductors [43-45]. The process takes place by tectonic fluid that infiltrates a highly fractured basement, subsequently reducing its effective normal stress and accumulating pore pressure through frictional heating inside the zone [46]. This triggers the occurrence of slip between rock bodies and leads to earthquake events [47]. Considering the undulating and hilly geomorphology in the study area and compressional forces towards the area, the fault is suspected to be a thrust fault. Another shallow fault was also identified to the east of the deep fault. Its position and orientation strongly agree with lineaments map [11], thus validating the MT results.

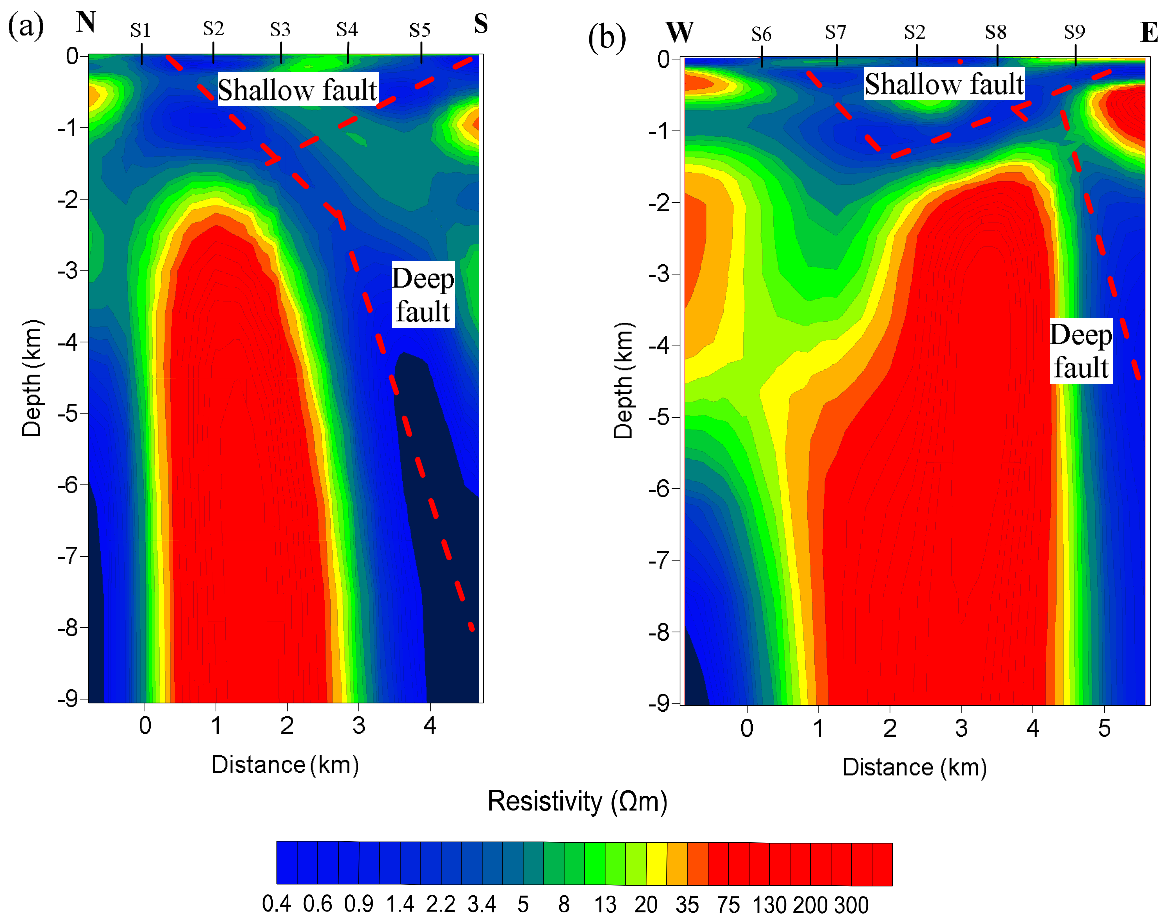

Figure 6. (a) NS and (b) WE resistivity profiles from MT survey in Lahad Datu

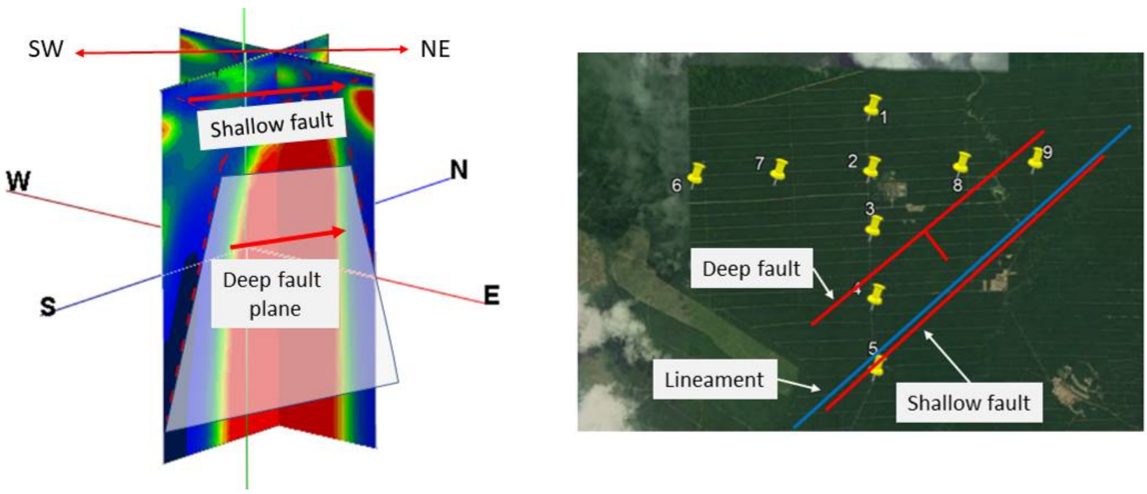

Figure 7. Suspected faults in Lahad Datu from MT data

Active faults pose a threat to humans, plantation, buildings, etc. Based on the model estimation, a series of earthquakes will occur in Lahad Datu anytime from now to year 2026. The deepest occurrence will be around 2022 at a depth of 33 km [48]. It is vital to equip seismic safety information to the local people by developing a comprehensive seismic hazard map. This study has provided the information on and structure of the active fault in Lahad Datu, which can serve as a reference in future studies.

CONCLUSIONS

A clear image of resistivity distribution in the Earth, which depicts the existence of a thrust fault in Lahad Datu has been produced by a high-resolution MT profile. The fault is orientated in the NE-SW direction and agrees with previous observations on the ground surface. As the fault is suspected to be active, further action should be taken for the safety of the locals and existing infrastructures.

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